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Spatial and Temporal Analysis of Fecal Coliform Distribution in Virginia Coastal Waters

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Spatial and Temporal Analysis of Fecal Coliform Distribution in Virginia Coastal Waters

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ABSTRACT

The collection of fecal coliform (FC) monitoring data in shellfish growing waters is primarily to assess public health risks from consumption of contaminated product. The data is also commonly used to assess the potential sources and loads of bacteria entering the aquatic system. This project is intended to extend traditional methods of developing these assessments, by applying an inverse modeling approach to improve the estimation of FC loads in the small watersheds typically contributing to shellfish growing waters in Virginia.

Many fecal contamination studies in lower Chesapeake Bay, Virginia, have conveniently focused on analyses over relatively small spatial and temporal scales. The potential sources of bacteria are numerous and the magnitude of their contributions is commonly unknown (Hyer and Moyer, 2004). The effects of stochastic events merely complicate the already difficult task of quantifying sources and loads in an inherently variable system (White et al., 2008). Instead of identifying and quantifying individual fecal bacteria sources, like deer or raccoons or domestic animals, it is herein proposed to analyze spatial and temporal patterns of fecal contamination on relatively large scales and quantify FC loadings based on land cover. The result would make it easier for managers to assign land-cover-based accountability to restore fecal contaminated environments.

Monitoring of FC concentrations throughout Virginia by the Division of Shellfish Sanitation (DSS) provided an opportunity to analyze FC levels from 1984 to the present and quantify FC loadings by type of land cover. There are three aspects in this study – spatial analysis of FC data, temporal analysis of FC data, and FC loadings quantification based on the findings from spatial and temporal analyses. GIS tools and a variety of statistical methods are used in combination with an inverse modeling approach. The modeling method was based on some basic concepts incorporated in the Watershed Management Model and the Tidal Prism Model currently used to develop Total Maximum Daily Load (TMDL) models for Virginia waters.

The core contributions of this dissertation are:
1) This study provided a thorough examination of FC monitoring data in Virginia coastal waters and described how contamination levels are expressed at different spatial and temporal scales. Analyses examined tidal effects, regional effects, land condition effects, and climate effects. Results not only inform management decisions, but also provide guidance for the subsequent quantification of fecal bacteria loadings.
2) Fecal bacteria loadings are quantified as a function of land cover. The model developed in this study avoids the problems associated with using highly varied and poorly documented FC production rates and population numbers. Although the model is simple, the magnitude of Fecal Coliform Event Mean Concentration (FCMC) values based on land covers effectively distinguished the seasonal FC loadings.

Spatial and Temporal Analysis of Fecal Coliform Distribution in Virginia Coastal Waters

I. INTRODUCTION

Today, protection from fecal microbial contamination is one of the most important and difficult challenges that environmental scientists face in trying to safeguard waters used for recreation (primary and secondary contact), public water supplies, and propagation of fish and shellfish (USEPA, 2005). Fecal contaminated waters not only harbor pathogens and pose potential high risks to human health, but they also result in significant economic loss due to closure of shellfish harvesting areas and recreational beaches (Rabinovici et al., 2004). As required by The Clean Water Act, states should survey waterways every two years and report those that fail to meet water quality standards to the U.S. Environmental Protection Agency (EPA). For effective management of fecal contamination in water systems, the sources must be identified and quantified prior to implementing remediation practices (USEPA, 2005).

Shellfish monitoring is intended to identify and quantify problems with fecal bacteria contamination.. The purpose of interpreting these monitoring data is to describe spatial and temporal patterns in contamination and to identify the key factors and processes that determine or influence those patterns (National Research Council, 1994; Mueller et al., 1997). These descriptions and identifications should eventually facilitate the process of quantifying the major sources of pollutants.

Many fecal contamination studies in lower Chesapeake Bay, Virginia, have been focused on relatively small spatial and temporal scale. While these studies have identified some causes and sources of contamination, and have related them to land use, hydrology, and so on, the situation still often like blind men describing an elephant in the old Indian tale. Even though each study can bring something new to the big picture, small scales probably prevent

researchers from looking at broad patterns, revealing overall characteristics of fecal contamination in lower Chesapeake Bay, and identifying key factors and processes.

Fecal coliform (FC) data collections from the Virginia Division of Shellfish Sanitation (DSS) provide an opportunity to analyze FC levels in large spatial and temporal scales. In Virginia, there have been no published studies analyzing FC data on such a large scale, covering all the Virginia coastal waters. Although large scales do not predict with certainty what one will actually find on a particular site at a given time, they can aid the prediction of how external factors or processes will alter certain patterns (Urban et al., 1987). Multivariate statistical methods are commonly used statistic tools and would be expected to reflect the effect from broad-scale physical processes or forcing functions on fecal contamination in the lower Chesapeake Bay.

Small watershed classification based on FC contamination processes, and how contamination levels are expressed at different temporal and spatial scales, can aid and guide successful management decisions and the process of mitigation. However, quantification of major fecal bacteria sources involves many challenges, one being the limited data sources for quantification. Another challenge is that the potential sources of bacteria are numerous and the magnitude of their contributions is commonly unknown (Hyer and Moyer, 2004). The effects of stochastic events are also often difficult to quantify spatially and temporally due to inherent variability in the systems (White et al., 2008).

Currently, there are two commonly used methods to quantify FC bacteria sources, that is, to estimate fecal bacteria loadings from land. One is through model simulation. Most models for simulating FC transport require data such as population numbers for human and animals and FC production rates. However, Hyer and Moyer (2004) mentioned that values of FC production rate and population number are very variable and poorly documented. Furthermore, most models estimated FC loads based on a watershed unit, that is, loads per

watershed. This creates challenges for managers to decide how to allocate pollution reduction responsibility among sources and to address the specific problems of a particular water body (USEPA, 2000). The second method to quantify fecal bacteria sources is called Bacteria Source Tracking (BST). A recently developed technology called Microbial source tracking (MST) is one type of BST. It has been used successfully to discriminate between ruminant and human fecal sources in fresh and marine waters (Boehm et al., 2003; Field et al., 2003; Gilpin et al., 2003). However, there are problems that need to be addressed, including the problems related to detection limits, temporal and spatial variability of markers (Simpson et al., 2002), among others. It is still not clear how effectively the MST technique can relate specific genes to measurement of fecal indicators in natural water (Shanks et al., 2006). Presently, there is no single method that has emerged as a definitive answer to the source identification problem (Kelsey et al., 2008).

This study attempts to quantify FC bacteria loadings based on different land cover types. Because of large uncertainties involved in the determination of FC loads from the watershed and the problems of BST technology in identifying FC sources, an alternative approach is to use inverse modeling. This approach involves quantifying FC loads from Virginia coastal watersheds based on observed FC concentration in relatively small tidal embayments at steady state. The quantification method is built on some basic concepts drawn from the existing Watershed Management Model (WMM) and Tidal Prism Model (TPM). The amounts of FC mean concentration from each land cover estimated from this study would be expected to help a state to assign land-cover-based accountability and establish a Total Maximum Daily Load (TMDL) allocation based on land-cover related sources.

This study will provide a thorough examination of FC data in Virginia coastal waters. The objectives of this study are to identify spatial and temporal patterns in lower Chesapeake Bay, to hypothesize reasons for the patterns, and to quantify land cover related sources for pollutant allocation purposes. By describing a general picture of fecal contamination in the

lower Chesapeake Bay, this project will provide some guidance on setting management goals based on a region's specific characteristics. Spatial patterns will categorize water bodies based on their contamination pattern similarity. Among the implications of this analysis might be a basis for decreasing the number of sampling stations within a given category of water bodies. Temporal patterns will hopefully offer some recommendations on the number of required samples for different times of a year. For example, less sampling in winter due to small variations in FC data and more sampling in summer due to high variations. The relationship between fecal contamination levels and environmental variables will provide a better understanding of the factors and processes contributing to fecal contamination. The quantification of land cover type fecal bacteria loads should help a state to allocate allowable loads to the contributing sources, so that water quality standards can be attained. In other words, the project should lead to more awareness about watershed influence on fecal contamination, and may lead to improved management decisions regarding FC monitoring design and pollution mitigation planning.

II. OBJECTIVES

The general goal of this study was to improve the understanding of fecal coliform (FC) spatial and temporal distribution in Virginia coastal areas and to quantify FC loads based on land cover. The study is based on the investigation of long term FC monitoring data and the analysis of large spatial and temporal scale FC distribution in Virginia coastal waters (regional scale, local scale, etc.). The specific objectives of this study are:

1. to describe FC spatial and temporal distribution patterns in Virginia coastal water;
2. to identify the factors and processes that determine or influence these patterns; and
3. to derive FC loads for major types of land cover

The following questions are addressed:

1. Is there any spatial pattern of FC distribution and how does it relate to environmental characteristics in Virginia coastal regions?

   This question was addressed from the aspects of:

   i) the areas where different fecal contamination levels occurred in general

   ii) regional comparisons among the areas around the Potomac River, the Rappahannock River, the York River, the James River, and the Eastern shore

   iii) comparison between different land-cover-dominated watersheds

   iv) relationship between environmental variables and FC contamination levels

2. What is the temporal pattern of fecal contamination and how does it relate to environmental variables in Virginia coastal regions?

   This question was addressed from the aspects of:

   i) tidal effects

   ii) climate effects

iii) the effects from changing land condition, such as impervious surface area or percentage change

3. How much FC load per unit area per inch of rainfall is transported through forest, urban, crop-pastureland?

   This question was addressed from the aspects of:

   i) introduction of inverse modeling approach

   ii) model verification

   iii) model sensitivity test

III. BACKGROUND AND LITERATURE REVIEW

III-1. Background

III-1-1. Fecal contamination – pathogens and their indicators

Waterborne microbial pathogens consist of three major groups, which vary in size from enteric viruses (20 to 80 nm diameter), through bacteria (0.5 to 3 [mμ]m long) to cysts and oocysts (4 to 18 [mμ]m long) of parasitic protozoa (Ferguson, 2003). Enteric viruses mostly derive from human feces and exist in sewage, such as bacteriophages (bacteria virus). Most of the pathogens, represented by *Escherichia coli* O157:H7, can cause gastroenteritis; they may also cause severe illnesses such as meningitis, encephalitis, paralytic poliomyelitis, and/or conjunctivitis (Ferguson, 2003). If domestic cattle or sheep are a major source within a watershed, *Campylobacter, Salmonella,* and *enterohemorrhagic E. coli* are likely to be the bacteria of prime concern (Donnison, 1999; Galland, 2001; Jones, 2000). However, it is difficult to examine the fate and transport of pathogens in water, soil, and groundwater because it is time-consuming and expensive for large-scale field experiments (Ferguson, 2003).

The potential presence of pathogens in the water usually can be estimated by measuring their indicator organisms' concentration. Since 1904, FC has been used to assess the presence of fecal contamination in water and foods. FC or its subgroup *E. coli* and *enterococci* are the most commonly used indicators. EPA recommended *E. coli* and *enterococci* to replace FC as indicators to monitor water quality of freshwater and marine waters, respectively (USEPA, 1986). This recommendation was based on the results of studies showing that elevated levels

of *E. coli* and/or *enterococci* groups exhibited a stronger correlation with gastrointestinal diseases than did FC (U.S. EPA, 1986). Another reason could be recent advances in the detection of *E. coli* which require only 24 hours or less detection time (Doyle and Erichson, 2006). Nevertheless, FC remains the most commonly used indicator of pathogen at present (Mallin et al., 2000; Rees et al., 1998).

Currently recommended criteria for shellfish harvesting waters are: 1) a 30-day log mean of 14 Most Probable Number (MPN) organisms per 100 milliliters (ml); and 2) the 90^{th} percentile shall not exceed an MPN of 43 for a 5-tube, 3-dilution test or 49 for a 3-tube, 3-dilution test (VDEQ, 2009). By comparison, the standard for drinking water is 0 FC/100 ml, while the swimming water standard is 200 MPN organisms per 100 ml. The Virginia Department of Environmental Quality (DEQ) has applied a translator equation to convert daily average FC concentrations to daily average *E. coli* concentrations (VDEQ, 2003). The translator equation is:

$$\textit{E. coli}\ \text{concentration} = 2^{-0.0172} \times (\text{FC concentration})^{0.91905}$$

III-1.2. Shellfish closure due to fecal contamination

Pathogens are one of the most commonly found pollutants in TMDL studies other than sediments and nutrients. Currently, there are about 112 square miles of estuary water in Virginia contaminated by pathogens because of elevated concentration of FC bacteria. Portions of some shellfish growing areas are either permanently or seasonally closed to direct shellfish harvesting due to the presence of either marinas or wastewater treatment facility discharges (VAVDH, 2007). DEQ released the Final 2008 305(b)/303(d) Water Quality Assessment Integrated Report, which listed about 40 percent of the state's waters as polluted, including rivers, lakes and estuaries (VADEQ, 2008). More than half of the newly listed impaired waters during the last two years were polluted by excess bacteria.

III-1.3. Regional difference of water quality in Virginia coastal area

Regional differences in land use, geology, and climate can lead to regional differences in water quality (Lapham et al., 2005). All major tributaries on the Western Shore of Chesapeake Bay are partially mixed coastal plain estuaries and have a deep basin near the mouth (Kuo et al., 1991). Kuo and Neilson (1987) reported that hypoxia occurred frequently in the deep waters of the lowest reaches of the Rappahannock and the York Rivers and rarely occurred in the James River even though it received the heaviest wastewater loadings among the Virginia estuaries. This difference has been attributed to the relatively strong gravitational circulation in the James River.

Bricker et al. (1999) characterized the eutrophic condition for the estuaries of the United States based upon a survey of over 300 experts on estuarine eutrophication. They listed three Virginia Rivers as follows: the James River as having a low eutrophic condition; the Rappahannock River as having a moderate eutrophic condition; and the York River has having a high eutrophic condition. A survey from 1985 to 2000 showed that two rivers in Chesapeake Bay with the highest sediment yield were the Rappahannock River (329 tons mi^{-2}) and the Potomac River (167 tons mi^{-2}). The James River had a moderate sediment yield (110 ton mi^{-2}), and the lowest yields were observed in Choptank River (23 tons mi^{-2}) from the Eastern shore region (Cronin et al., 2003). Recent studies have shown that the Rappahannock River delivers more sediment per square unit of watershed than any of the other tributaries of the Chesapeake Bay. A York River study indicated that little sediment from the upper watershed reached the estuary. Water quality may be more affected by locally derived sediments near the estuary. Therefore, the improvement of water quality in the York River estuary may be largely independent of soil conservation practices implemented extended distances upstream (Herman, 2001).

III-2. Literature Review

III-2-1. Spatial Pattern of Fecal contamination

The presence of a spatial gradient in fecal contamination levels among monitoring stations may reflect the effects of physical processes or "forcing functions" that create gradients in the physical environment (Legendre and Troussellier, 1988). Mallin et al. (2000) showed that there was a spatial pattern of decreasing enteric bacteria away from upstream areas, and both FC and *E. coli* abundance were inversely correlated with salinity within five estuarine creeks in North Carolina. This pattern has also been noted along the Texas coast (Goyal et al., 1977; Esham, 1994). Mallin et al. (2000) gave several possible reasons to explain the pattern, such as the effect from salinity and location. A number of experiments have demonstrated that FC survival is shorter in waters of greater salinity (Hanes and Fragala, 1967; Evison, 1988; Solic and Krstulovic, 1992). Also, higher salinity creek stations are probably better flushed and diluted than low salinity headwaters stations. Finally, headwaters stations in general are closer to pollution sources than high salinity creek mouth stations. Burkhardt et al. (2000) also found that the levels of indicators and pathogens occurring in effluents decrease with increasing distances from the point of discharge due to factors such as dilution, sedimentation, predation and inactivation.

A study in the Geum River located in South Korea shows that the FC concentration of combined sewer overflow was the highest, followed by combined agricultural land use–forestry watershed, and was lowest in a forestry land use dominated watershed (Kim, 2005). Line et al. (2008) compared geometric mean FC levels between two sites, whose primary land use at one site was residential and industrial, and for the other was national forest. The results showed that the geometric mean FC levels in residential and industrial sites ranged from 593 to 2096 MPN/100ml, which was much higher than the mean in national forest site, 191 MPN/100ml. Monitoring

studies of coastal North Carolina watersheds by Cahoon et al. (2006) and Mallin et al. (2000) both mentioned development as the cause of increased levels of FC in coastal waters. However, Mallin et al. (2000) emphasized that imperviousness, storm water, or nonpoint source related issues were the primary factor that leads to higher fecal contamination levels, whereas Cahoon et al. (2006) indicated that septic systems were the primary factor in rapidly developing area.

III-2.2. Temporal Pattern of Fecal contamination

The presence of temporal gradients may be highly affected by tide, climate, or temporally related factors. The variation in these factors would have a strong effect on surface runoff and river flow and, hence, on the FC concentration in the receiving waters. Mallin0 et al. (1999) has shown that lowest FC abundance occurs near high tide, and highest abundance occurs at or near low tide in tidal creeks in North Carolina. These authors attributed this pattern to decreases in salinity of over 20% between high and low tides. This difference occurred simultaneously with sharp increases in FC concentrations and reintroduction of FC bacteria into water column by tidal stirring (tidal resuspension).

The levels of fecal contamination in coastal waters may change seasonally with temperature, rainfall, and other influences (Wyer et al., 1995; Ferguson et al., 1996). This may be particularly pronounced in areas with non-point sources of pollution that contribute to both increased levels of nutrients and microbial pathogens in coastal waters (Lipp et al., 2001). In the coastal North Carolina, FC concentrations were the highest during the spring and the summer, but lowest from December to February (Line et al., 2008). In Charlotte Harbor, Florida., FC indicator concentration tend to be greatest in August and lowest in December through February (Lipp et al.,

2001). Warm weather FC concentrations were often much greater than cold weather concentrations (Novotny and Olen, 1994; Schueler, 1999a), apparently due to greater survival and regrowth (Howell et al., 1996).

While seasonal infections and excretion in a population may influence pollutant loads to receiving waters (Jaykus et al., 1994), climate may also influence the distribution and survival of certain microorganisms. Concentrations of FC bacteria, *enterococci*, and *coliphage* in the water column increased significantly with increased rainfall in the 7 days preceding sample collection (Lipp et al., 2001). Furthermore, all indicators (except *C perfringens*) showed a significant positive response to increased river discharge in the Peace and Myakka Rivers in Florida (Lipp et al., 2001). Others have also demonstrated the importance of rainfall and stream flow in the loading of fecal indicator organisms to coastal waters (Goyal et al., 1979; Wyer et al., 1995; Ferguson et al., 1996; Weiskel et al., 1996; Mallin et al., 2001). Rain events can disturb stream sediments and release sediment-bound FC into the water column (Struck, 1988). In New Orleans, it was observed that significant rainfall events up to 2 to 3 days prior to sample collection can affect FC levels (Barbe et al., 2001).

However, discrepancies were likely to occur between expected and observed FC concentration for any given event or day. Past studies using empirical models, have shown that these discrepancies were reduced when grouping estimates over longer time periods, such as groups of storms or seasons (Chui, 1981; Little et al., 1983). Precipitation analysis in New Orleans (Barbe et al., 2001) showed a reduction in mean total annual rainfall during the study period amounting to nearly one-third of the typical mean total annual rainfall for the area. Lower FC concentrations observed may be due to uncharacteristic drought conditions rather than decreased pollution.

III-2.3. Relationship between different variables and water quality

As geographic information system (GIS) has been developed into a powerful research approach, many studies have been relying more heavily on land use or land cover as broad, geographic scale predictors or indicators for aquatic conditions (Hunsaker and Levine, 1995; Allan and Johnson, 1997; O'Neill, et al., 1997). Land uses within a watershed can account for much of the variability in stream water quality (Omernik 1977). In the following several paragraphs, potential influences from different land covers are reviewed.

Urban Land: Populated areas are closely associated with impervious surface areas, such as roofs, roads, driveways, sideways, and parking lots. Mallin et al. (2000) found that the percentage of impervious cover could explain 95% of the variability of geometric mean FC density in several estuarine systems in North Carolina. Pet wastes from dogs and cats are another important fecal pollution source from urban areas (Kelsey, 2004). After pet waste reaches the impervious land, these land surfaces provide a quick way to transport the microorganisms inside the wastes into the downstream water systems.

Agriculture and Pastureland: In many types of farming systems, animals or poultry are raised confined in barns, and their manure is stored, sometimes in extremely large holding tanks, for several months prior to release onto agricultural lands or pasture lands (Lu et al., 2005). Pathogens, especially those which are capable of surviving for longer times in manure, could possibly find their way into the water from these sources. Treated sewage sludge as by-products from wastewater treatment plants is an organic-rich alternative to fertilizer to improve soil properties. Many organisms can survive for several months and multiply in sludge-amended soils (Gibbs et al., 1997; Tierney et al.,

1997). There are growing concerns that such land-applied manures or treated sewage sludge are making their way through either land runoff or airborne transmission into adjacent water systems and degrading water quality (Carrington et al., 1998).

Forest: Wildlife in the forest, such as the deer, raccoon, and birds, are the primary contributors to fecal contamination. The fecal bacteria loading from forested land is the lowest in comparison with other land uses, such as combined sewer overflow (urban), agricultural land, and separate sewer overflow (suburban) (Kim, 2005). Mallin et al. (2000) described the benefits to water quality of having vegetation in a watershed as following: "Lateral flow through vegetation settles out solids and associated bacteria, vegetation utilizes nitrogen and phosphorus through uptake, downward percolation achieves further nitrogen removal through denitrification by soil bacteria, and soil particles adsorb phosphate, ammonium, enteric bacteria, and other pollutants."

Wetlands: The use of wetlands for wastewater treatment was stimulated by a number of studies in the early 1970s that demonstrated the ability of natural wetlands to remove suspended sediments, nutrients, and fecal bacteria, from domestic wastewater (Nichols, 1983; Godfrey et al., 1985; Knight, 1990). However, a study in a southern California marsh suggests that the marsh could be a source of fecal bacteria loading to the coastal ocean (Grant et al., 2001). A potential tradeoff is identified between restoring coastal wetlands and protecting beach water quality (Grant et al., 2001). The debate regarding wetlands as a source/sink for nutrients and sediments, as well as fecal bacteria (Grant et al., 2001) has yet to be resolved. Tidal wetlands' role in FC transport could be embodied in the net sediment transport between tidal wetlands and adjacent coastal waters (Huang, 2005).

Runoff: As rainwater passes over a land surface, anything on the land surface which could be carried, is frequently entrained and carried into the receiving waters. This pollutant-carrying ability could dramatically increase fecal contamination levels in receiving waters after rainstorms (Crabill et al., 1999; Jin et al., 2000). Three to seven days were needed for the elevated indicator organisms to return to background levels in the water column and sediments in the Lake Pontchartrain estuary in southeastern Louisiana (Jeng, 2004). Hydrological characteristics vary significantly in different land uses. In a typical forested ecosystem, approximately 40% of the runoff is returned to the atmosphere by evapotranspiration and approximately 50% infiltrates into the soil, with the remaining 10% returned to receiving waters via surface runoff (e.g., Dunne and Leopold, 1978; Harbor, 1994; Arnold and Gibbons, 1996). In a developed watershed with 16% to 85% impervious cover, approximately 15–75% of the rainfall was estimated to be returned to the receiving waters (Holland, 2004). These data suggest that for rainfall events of similar magnitude, the volume of runoff returned to the water was 3–25 times greater in developed watersheds in South Carolina than in forested watersheds.

Residence Time: Zimmerman (1976) defined residence time as the time taken for an element in a water body to reach the outlet. It is an important determinant of water quality because, in combination with rates of chemical reaction, boundary loss, internal decay or die-off, it determines the biogeochemical fate of the contaminants (Hilton et al., 1998). Since Virginia coastal areas are influenced by tide, part of the water flowing out returns with the flood tide. In this study, the return ratio was set at the same range suggested by previous studies for Virginia coastal embayment as 0.7 (Kuo et al., 1998). The classical empirical model of lake eutrophication (Vollenweider, 1976) describes algal biomass as a function of phosphorus loading rate scaled by the hydraulic residence time. Since this paper has been published, water retention time or flushing rate has been

widely applied in biological, hydrologic and geochemical studies (Monsen et al., 2002). From a management perspective, it is important to know the time scale for a pollutant discharged into a water body, and then transported to another location or out of the system under different hydrological conditions (Shen and Haas, 2004). Residence time is a convenient integrated measure of transport that can be used to validate more sophisticated water quality analyses (Hilton et al., 1998).

III-2.4. FC loading estimation

Currently, there are two approaches to quantify fecal bacteria pollutants from land. The first approach is using watershed-scale models, as suggested by the EPA, to generate loading from different land use based on hydrological variation. The watershed model simulates the daily FC loads from the watershed and discharges to the receiving water where the hydrodynamic model is used to simulate FC transport in the water column of the receiving waters. Most watershed models are lumped parameter models and are mainly driven by precipitation. The accuracy of precipitation is quite important to determine the performance of watershed models. The estimation of fecal bacteria amount by these watershed models also highly depends on the input data, such as land use distribution, hydrologic data, livestock, wildlife, and human population estimates, and FC production rate from each individual human and/or animal. FC production rates, however, generally are highly variable and poorly documented (Hyer and Moyer, 2004). Population levels are commonly unknown for humans, pets, and wildlife, and the proportion of the population that contributes to the instream FC load is also generally unknown (Hyer and Moyer, 2004). The variability of data leads to large uncertainty involved in the estimation of FC loads from watersheds.

The way to "resolve" the problem of uncertainty is through model calibration. But model calibration is subjective and often relies on visual comparison of model results against observations (Shen et al., 2006). It is assumed that observed fecal data in the water comes from well-mixed conditions, but in estuarine settings this is not always true. After careful calibration, it is still difficult to answer questions as to whether or not the derived solution is correct, how many other solutions are equally viable, and what degree of uncertainty is associated with loading estimation (Shen, et al., 2006). Even though some models, like HSPF, have been demonstrated to be an effective tool for simulating FC transport (Shen et al.,2005), the variation in the data sources and uncertainty involved in model calibration limit the capability of models to successfully identify and quantify FC sources.

Another way to identify and quantify the sources of fecal bacteria is to use Microbial Source Tracking (MST). It has been used successfully to discriminate between ruminant and human fecal sources in fresh and marine waters (Boehm et al., 2003; Field et al., 2003; Gilpin et al., 2003). For example, sources of fecal pollution in Virginia's Blackwater River have been identified using antibiotic resistance analysis (ARA), a type of MST, showing that livestock contributed the highest percentage of isolates (47.6%), followed by wildlife (29.1%), and human (24.9%) (Booth et al., 2003). The results from this research are being used to develop TMDL project allocations for FC in the Blackwater River. While results from MST studies could help significantly in the implementation of best management practices, there are a number of problems that need to be addressed, including the problems relating to detection limits, reproducibility of the assays, and temporal and spatial variability of markers, (Simpson et al., 2002). Beside these problems, it is still not clear how the MST technique can relate specific genes to measurement of fecal indicators in natural water (Shanks et al., 2006). So far there is no single method that has emerged as a definitive answer to the source identification

problem (Kelsey et al., 2008). Therefore one must be very careful when applying an estimated quantification result from MST methods.

IV. SPATIAL AND TEMPORAL ANALYSIS

IV-1. Introduction

Although many studies have tried to reveal the relationships between environmental variables and fecal contamination (Mallin et al., 2001; Holland et al., 2004; Kelsey et al., 2004), the subject remains the focus of numerous investigations.

In this research, I addressed the following concerns: 1) Since the study sites are located in the coastal zone, it would be interesting to investigate the relative effect of tides and seasons on fecal contamination level. 2) Since land uses have characteristic FC sources, is it possible to characterize the FC load arising from various land covers? 3) Impervious land surface areas (including roads, roofs, parking lots, etc.) are often used as an indicator of human influence on the environment. Is there a threshold in impervious cover that can be related to significant increases in fecal contamination? 4) If land cover or land surface conditions do have impact on fecal contamination levels, what about other environmental variables such as slope and residence time? 5) Will regional differences surrounding major rivers in Virginia estuaries lead to regional difference in fecal contamination levels? Could regional characteristics explain the difference? 6) In addition to land condition, climate plays a big role in pollution issues. Beyond the general understanding of rainfall, temperature, and other factors' influence on fecal pollution, to what extent can their affect be seen in Virginia monitoring data? 7). Not all the variables contribute equally to the fecal contamination levels. In Virginia, what are the most important variable for prediction of fecal pollution?

This study seeks to advance understanding of spatial and temporal characteristics of fecal contamination in Virginia tidal waters. It is expected that the results from this study will provide guidance in the management and remediation of fecal pollution in Virginia coastal regions.

IV-2. Materials

IV-2.1 Site Description

This investigation is primarily concerned with the effects of non-point source inputs on coastal pollution. This study is focused on sites located in Virginia's Coastal Plain, as shown in Figure IV-2.1.1. Virginia's Coastal Plain is bordered by the fall line to the west and by the Atlantic Ocean to the east, with the Chesapeake Bay and its tributaries in the middle. The Coastal Plain varies in topography from north to south. The western Coastal Plain consists of the three peninsulas formed between the four major tributaries of the Chesapeake Bay; the Potomac, the Rappahannock, the York and the James Rivers. The Eastern shore, separated from the mainland by the Chesapeake Bay, exhibits little topographic relief. The subtle differences in topography and the variety of fresh, brackish, and saltwater systems from ocean and inland bay to rivers, ponds and bogs, have contributed to the great variety of natural communities found on the Coastal Plain. The soil of the coastal plain is dominantly deep, moist Aquults and Aqualfs (McNab and Avers, 1994). Rainfall in the region averages 110 cm per year, and the average temperature ranges from 13 to 14 C (McNab and Avers, 1994). The growing season generally lasts between 185 and 259 days (shortest in the northern portion, longest in the city of Virginia Beach) (Woodward and Hoffman, 1991). Most streams are small to intermediate in size and have very low flow rates (McNab and Avers, 1994). Due to its position in the middle of the East Coast, Virginia's coastline is critical to hundreds of

species of migrant birds (Hill, 1984). The Delmarva Peninsula and Cape Charles, in particular, are one of the most important areas for migratory bird staging in North America (Hill, 1984; Watts and Mabey, 1994). Since major improvements to wastewater treatment plants occurred in the 1970s and early 1980s (Barber et al., 1993), most major point source problems were controlled by 1983. Over the years, many of the Commonwealth's wastewater treatment facilities have become models for the industry, receiving national accolades for their water cleaning technology (Barber et al., 1993).

IV-2.2 FC Monitoring Data

Fecal coliform data used in this study were collected by the DSS monitoring surveys of Virginia shellfish growing waters from 1985 to 2003. Samples were taken at any given station once per month varying from 2 years to 23 years. Department of Shellfish Sanitation also provided the GIS layer for the location of each sampling station. More than 85% of the DSS stations have sample periods longer than 15 years. In total, there are about 2100 sampling stations distributed throughout the lower Chesapeake Bay. Stations were chosen with sample periods longer than 5 years. The geometric mean was calculated for each station each month to represent monthly FC levels because the data mainly contain numerous small values with a few very large values skewing the data distribution. Mean FC abundance for the water of each watershed is represented with the geometric mean of all samples collected during the studied sampling period. Annual mean FC levels in Virginia coastal regions are determined by the geometric mean of all available stations in Virginia coastal waters for each year.

IV-2.3 Environmental Data

The selection of variables representing environmental characteristics focuses on those with potential influence on fecal pollution. These include watershed morphology (i.e. land area, surface water area, and shape of watershed), land use/land cover information, land surface condition (slope, runoff potential), as well as hydrodynamic characteristics (drainage density and embayment water residence time).

Land cover: The National Land Cover Data (NLCD) served as the land cover information dataset. All land use classifications were reclassified into five by grouping similar land use categories: developed, forest, pastureland, cropland, and wetland. With ArcMap 9.3, the area of different land covers in each watershed was derived by extracting land use information from NLCD GIS layers.

Watershed area, Water area, and Water volume: Water area and watershed area for studied areas were calculated from the NLCD dataset with the help of ArcMap 9.3. Water volume for each watershed was estimated and obtained from bathymetric data using NOAA Hydrographic Surveys and National Ocean Service data.

Slope, Drainage density, and Eccentricity: The slope estimate for each watershed was the averaged value from all the individual slopes of grid cells inside the watershed based on the USGS digital elevation model (DEM) dataset. Drainage density was calculated by dividing the total length of the stream within a watershed by watershed area based on the National Hydrography Dataset (NHD). Another hydrograph parameter considered is watershed Eccentricity (Black, 1972) which takes into consideration the unique shape of watersheds. Watershed eccentricity is an easily measured, meaningful, and useful expression of watershed shape which reflects maximum peak flows and time parameters of the hydrograph (Black, 1972). Eccentricity equation is shown here:

$$\tau = (|L_c^2 - W_L^2|)^{0.5} / W_L$$

Where τ = watershed eccentricity, a dimensionless parameter; L_C = length from the outlet to center of the watershed, W_L = width of the watershed perpendicular to L_C and at the basin's center of mass, both in the same units. Low values of τ are found to be associated with high flood peak potential and high values of τ with low flood peaks (Black, 1996).

Soil: The State Soil Geographic (STATSGO) database was used to determine the hydrologic soil group for the analysis areas. The primary soil attribute used in STATSGO is the hydrologic soil group (A, B, C, D and A/D, B/D, and C/D). Hydrologic group is defined by National Soil Survey Handbook as a group of soils having similar runoff potential under similar storm and cover conditions. Group A is characterized by low runoff potential soils, which have a high infiltration rate even when thoroughly wetted. Group B soil has a moderate infiltration rate when thoroughly wetted. Group C has a slow infiltration rate when thoroughly wetted. And Group D is high runoff potential soils, which have a very slow infiltration rate when thoroughly wetted. Only soils that are rated D in their natural condition are assigned to dual classes A/D, B/D, and C/D. Here, Group A and Group B will be regrouped together to represent low runoff potential soils. The other groups (Group C, D, A/D, B/D, C/D) will be regrouped together as high runoff potential soils. Soil drainage condition in a watershed will be determined by total area of low runoff potential soils divided by total area of high runoff potential soils.

Residence time: Part of the volume of water that enters an estuary during the flood tide is made up of water that left the estuary on the previous ebb tides. The remainder is water that one may think of as "new" ocean water, and since this portion is what is available for dilution of pollutants inside the estuary an estimate of its amount is an important part of a one-dimensional analysis (Fisher, 1979). The residence time, *RT*, is an estimate of time required to replace the existing pollutant concentration (or water) in a system; it can be calculated as follows: $RT = V_b / Q_b$, where V_b is mean volume of the embayment, Q_b is the quantity of mixed water that leaves the bay on the ebb tide that did not enter the bay

on the previous flood tides (m^3 per tidal cycle);. In a steady-state condition, the mass balance equations for the water can be written as follows: $Q_b = Q_o + Q_f$, Q_f is total freshwater input over the tidal cycle (m^3); Q_o is the volume of new ocean water entering the embayment on the flood tide, which can be determined by the use of the ocean tidal exchange ratio β as: $Q_o = \beta * Q_T$, where Q_T is the total ocean water entering the bay on the flood tide (equal to the multiplication of water surface area and tidal range). β is defined as the ratio of new ocean water to total volume of water that enter the estuary during a flood tide (Fisher, 1979). Usually, the return ratio was set as 0.7, as previous studies suggested for Virginia coastal embayment (Kuo, et al, 1998).

IV-3. Methods

IV-3.1 Tidal and seasonal effects

The DSS FC database not only stores observed FC data, but also provides the tidal information for selected sampling stations. The DSS code tidal levels with 9 assigned numbers, as shown in Figure IV-3.1.1. These codes are: 1 (high tide-1.4 hours ebb), 2 (1.5 hours ebb-2.9 hours ebb), 3 (3.0 hours ebb-4.4 hours ebb), 4 (4.5 hours ebb-low tide), 5(Low tide - 1.4 hours flood), 6(1.5 hours flood-2.9 hours flood), 7(3.0 hours flood-4.4 hours flood), 8(4.5 hours flood-high tide), and 9(no data). Since not all the stations have recorded tidal information, only the stations with tidal information were chosen for this study. In order to determine the tidal effects on FC concentration levels, FC data were separated into two groups according to the tidal levels during the sample collecting time. One group includes all FC data collected at high tide (code 1 and code 8) and another group includes all FC data collected at low tide (code 4, and code 5). For each month, at each chosen station, FC geometric mean concentrations at high tide and low tide are treated as a pair of data. A non-parametric 1-sample Wilcoxon signed-rank test, was applied to the

paired FC geometric mean concentrations both at high and low tide, since the difference in FC concentration between high and low tide did not follow a normal distribution curve for the paired-t test. Null hypothesis is that there is no difference between FC concentration medians between low tide and high tide. The alternative hypothesis is that FC concentration median in low tide is greater than median in high tide. A significance level α was set as 0.05. Using the same stations, FC data were grouped into summer and winter seasons. Summer was defined from July to September, while winter from January to March. The 1-sample Wilcoxon signed-rank test was also applied to the paired FC geometric mean concentration in summer and winter. For each station, FC concentration at low tide in summer was compared to FC concentration at low tide in winter. Similarly for high tide, FC concentration at high tide in summer was compared to high tide in winter. The alternative hypothesis is that FC concentration in summer is greater than in winter. The difference in fecal contamination levels due to tide was compared to the difference due to seasonal change by looking at their distributions using box plots.

IV-3.2 Re-define study sites in Virginia coastal regions

Instead of looking at the whole Virginia coastal region, the areas with relatively high fecal contamination levels were selected as the focus regions for further analysis. Empirical Orthogonal Functions (EOF) method was applied to redefine the study sites where high fecal contamination levels occurred. This statistical method decomposed FC data into spatial components and associated temporal components. Targeted FC data matrix A (mxn) can be constructed by vectors U(mxm), V(nxn), and S(mxn) as shown as:

$$A = USV^T$$

In this matrix the columns of U describe most of the space-dependent variation (this is the Empirical orthogonal function (EOFs), sometimes called an Eigenvector or Principal

Component loading pattern). The columns of V capture most of the time-dependent variation associated with space (the Principal Component or PC, sometimes called amplitude of time series or Expansion Coefficients). So EOFs tell us how the time-dependent variations vary within space and PCs tell us how the spatial modes vary with time. For ease of expression, in this study the name "spatial component" was used to represent EOF as spatial variation and "temporal component" was used to represent PC for temporal variation. The diagonal elements of S indicate the eigenvalues (λ_i). The fraction of total variance explained by the *i*th EOF (spatial component) or PC (temporal component) is simply given by:

$$\frac{\lambda_i}{\sum \lambda_j}$$

Therefore the fraction of the variance explained by the first *k* (which explain most of data variation) of the *EOF or PC is given by :*

$$v_k = \frac{\sum_1^k \lambda_i}{\sum \lambda_j}$$

No other linear combination of first *k* predictors can explain a larger fraction of the variance than the first *k* principal components. Usually, most of the variance of a spatially distributed series is in the first few orthogonal functions whose patterns may then be linked to possible dynamic mechanisms. That is, by summing the first few components (let's assume first 3 components, SUM = $U_1S_1V_1 + U_2S_2V_2 + U_3S_3V_3$), the total variance of matrix A would be mostly explained by matrix SUM (Emery and Thomson, 2001; Hartmann, 2010; Bjornsson and Venegas, 1997).

The data for EOF analysis (chosen for sample period longer than 5 years) was the monthly FC data set, which contained monthly geometric mean FC concentrations from

the year 1981 to 2003, at only stations located inside of river branches (not in the main channel). This totaled 1460 monitoring stations. This set of observed FC concentration values, in general, reflects both spatial and temporal information, which contains where and when the sample has been collected. The data matrix for EOF was constructed with 1460 stations by 12 months. Each element in the matrix represented the geometric mean of FC concentration for a specific month at a specific station. The created data matrix was run using the statistic software Primer 6.0. Spatial components and associated temporal components were analyzed to divide receiving waters into high, middle, low FC contaminated regions.

Cumulative frequency graphs were used on these different contaminated level regions for the comparison. The non-parametric Kolmogorov-Smirnov test (KS-test) was performed to determine whether each pair of datasets (high, middle, and low FC contaminated regions) differed significantly based on their cumulative frequency distribution. The advantage of the K-S test is that there is no assumption about the distribution of data. The significance level of K-S test was set as 0.05. The null hypothesis is that two data sets follow the same distribution. The alternative hypothesis is that two data sets didn't follow the same distribution if the test statistic, D, is greater than the critical value D_∂ obtained from the equation for large sample size:

$$D_\partial = 1.36\sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

IV-3.3 FC distribution among different land cover dominated watersheds

Among upstream watersheds, single land-cover-dominated watersheds were chosen to look at the effect of different land covers on fecal contamination levels in their receiving waters. It was assumed that there should be at least 4 or 5 watersheds in each type of single land-cover dominated watersheds group in order to have sufficient data points to examine the effects of different land covers. The standard for a watershed to be called a single land-cover-dominated watershed is defined as following: a"Forest dominated" watershed is one with forestland occupying more than 80% of the entire watershed area. A"Crop-Pastureland dominated" watershed is one for which the cropland and pastureland together occupy about 70% of the entire watershed. An"Urban dominated" watershed is one where more than 70% of land has been developed. The numbers of 80% for forest, and 70% for urban and crop-pastureland were determined by the frequency of their occurrences in the watersheds of coastal Virginia. In the end, there are 4 watersheds whose percentages of forest were more than 80%. There are 5 watersheds whose percentages of urban were more than 70%, and another 5 watersheds whose percentage of crop-pastureland exceed 70%. NLCD 1992 land cover data set was used to derive the percentage of occupation by each land cover for each watershed. FC concentration values from DSS water quality monitoring stations located in the receiving waters of chosen watersheds were extracted from the period between 1/1/1990 and 12/31/1994. A combination of the box plots and cumulative frequency graphs were used on these extracted FC concentration values for the comparison between different land-cover-dominated watersheds. Their differences were tested by performing the non-parametric Kolmogorov-Smirnov test (KS-test) on their cumulative frequency distribution. The significance level of K-S test was set as 0.05 as usual.

IV-3.4. The effects of impervious land surface on fecal contamination

The Mid-Atlantic Regional Earth Science Applications Center (RESAC) at the University of Maryland provides highly detailed impervious surface maps, which span the Virginia coastal watersheds. Smith et al (2003) noted "The RESAC has selected two eras for land cover mapping; one centered on 1990 and the other on 2000. Eras are used rather than specific years because adequate data are not always available for the target year. The RESAC team has advanced the capabilities of the Landsat series of satellites to measure the amount of impervious surface within a 30-m pixel. Impervious surfaces include all surfaces (man-made or natural) that inhibit infiltration by rainfall. The sub-pixel classification technique used by the RESAC assigns a percentage value (between 0 and 100%) to each location based on the spectral measurements of the ETM+ sensor." The new maps have found applications in the study of surface water redistribution, runoff and pollution (Goetz et al., 2003). An impervious percentage for each watershed was derived by overlaying upstream watersheds boundaries on the RESAC layer using ArcMap 9.3.

An impervious surface area analysis was conducted on the upstream watersheds. Since impervious data centers on 1990 and 2000, 5 years of FC monthly data surrounding 1990 (1988 to 1992) and 2000 (1998 to 2002) were extracted to represent the fecal contamination levels in 1990 and 2000, respectively. From these five years, a subset of FC data was selected for which rainfall occurred within four days before the sampling date. The FC geometric mean concentration in 1990 was derived by averaging FC data from 1988 to 1992, and the FC geometric mean in 2000 was averaged from 1998 to 2002. Thresholds in the relationship between impervious surface percentage and FC levels in the post-rainfall data sets for 1990 and 2000 were identified by nonparametric changepoint analysis (nCPA) (Qian, et al., 2003). The method was proposed by Qian et al., for detection of environmental thresholds. Changepoint analysis works best when

stressor-response relationships are nonlinear or heteroscedastic, properties very common to ecological data (King and Richardson, 2003). This analysis is based on the idea that a structural change in an ecosystem (indicating a threshold) may result in a change in both the mean and the variance of an ecological response variable (King and Richardson, 2003). It tries to find threshold values by separating the response variable into two groups, which have the greatest difference in their means and/or variances. The deviance (Venables and Ripley, 1994), a measure of homogeneity, is defined for a continuous variable, as:

$$D = \sum_{k=1}^{n} (y_k - \mu)^2$$

where D is the deviance, n is the sample size, y_k is the observed value, and μ is the mean of n observations. Each possible changepoint is associated with a deviance reduction:

$$\Delta_i = D - (D_{\leq i} + D_{>i})$$

Where: D is the deviance of the entire data set; $D_{\leq i}$ is the deviance of first i observed values; and $D_{>i}$ is the deviance of the remaining observed values, where $i = 1, \ldots, n$. The changepoint r is the i value that maximizes Δi : $r = max i \Delta i$. Nonparametric changepoint analysis estimates uncertainty in the changepoint using a bootstrap simulation. With bootstrap simulations repeated 1000 times, a distribution of change points is estimated and illustrated with a cumulative probability curve that describes the probability of a change-point occurring at various levels of disturbance (Bilkovic et al., 2007). When probabilities of Type I error for potential changepoint were less than 0.05, the cumulative probability curves were assumed to accurately assess the likelihood of an ecological threshold occurring. Change-point analyses were conducted in S-Plus using the custom function "nopar.chngp." Detailed descriptions of this method are found in Qian et al., (2003) and King and Richardson (2003).

IV-3.5 FC distribution in different river regions

FC stations located in the upstream receiving waters were grouped as the Potomac River stations, the Rappahannock River stations, the York River stations, the James River (including Lynnhaven area), and the Eastern shore stations according to their location. The differences in FC distribution among these groups were shown by a FC concentration frequency analysis using box plot and cumulative frequency distribution graphs with all available FC data from DSS using Minitab 5.0. The median values, and 25^{th} and 75^{th} percentiles were plotted for easy comparison between the four regions. The cumulative frequency distribution curve was plotted against the boxplots to help with analysis. The non-parametric Kolmogorov-Smirnov test (KS-test) was performed to determine whether each pair of datasets differed significantly based on their cumulative frequency distribution. The significance level of K-S test was set as 0.05. The null hypothesis is that two data set follow the same distribution. The alternative hypothesis is that two data set didn't follow the same distribution if the test statistic, D, is greater than the critical value D_{∂}.

In order to show the linkage between environmental characteristics surrounding the Rappahannock River, the York River, the James River, and the Eastern shore to their own fecal contamination condition, Principal Component Analysis (PCA) was applied in their upstream watersheds with a total of 14 variables. The variable included: soil condition, slope, drainage density, eccentricity, residence time, ratio of watershed area divided by water area, watershed area, water area, water volume, wetland percentage, cropland percentage, pasture percentage, forest percentage, and developed percentage. Land cover used here comes from NLCD 1992 land cover dataset. Since only the southern side of the

Potomac River was located in Virginia, it was not included for its environmental characteristic analysis. The results from PCA were used to explain fecal contamination level differences among the four regions.

IV-3.6 Climate effect

The Chesapeake Bay Program watershed model (Phase V) uses an hourly rainfall data set for the period from 1/1/1985 to 12/31/1998. Annual rainfall data for this analysis were obtained by summing all the hourly rainfall records of each year. The annual rainfall amounts were related to the yearly FC average levels in Virginia coastal waters from 1985 to 1998. The yearly FC average levels were derived from the geometric mean of all the stations for all measurement dates of each year. Correlation coefficients were estimated for rainfall and FC by Pearson Correlation method using MINITAB 5.

DSS not only provides FC data, but also precipitation intensity for each sampling station for the 7 days before any sampling date. Precipitation was grouped into 5 classes according to the rainfall intensity provided by DSS. Precipitation in the first class is drizzle, the intensity of which range from 0 to 0.4 inches/day. The second class is medium rain, ranging from 0.4 to 1 inches/day. The third class is large rain, from 1 to 2 inches/day. The fourth is pouring rain, from 2 to 4 inches/day. And the last one is any rainfall greater than 4 inches/day. The classification is based on the protocols of the China Meteorological Administration. FC concentration variation was graphed with each rainfall group for 1 day, 2 days, 3 days, and 7 days before sampling dates.

The study on temporal variability of fecal contamination levels was only conducted on DSS water quality monitoring stations located in receiving waters of upstream watersheds. There are 487 water quality monitoring stations in the receiving waters of

upstream watersheds. EOF method was applied on a created data matrix with arrays of 487 (stations) x 12 (months). Analysis of the data matrix was run using Primer 6.0 software. Monthly precipitation, air and water temperature, and flow discharge, as shown in Table IV-3.6.1, were hypothesized to be correlated with principal components (PCs). Monthly precipitation and temperature was derived by averaging monthly precipitation and temperature data in three cities (Norfolk, Richmond, and Williamsburg) extracted from National Climatic Data Center with the aid of Climatology Office in University of Virginia. Available precipitation and air temperature data in Norfolk is from 1/1/1946 to 12/31/2008, from 8/1/1948 to 12/31/2008 in Williamsburg, and from 8/1/1948 to 12/31/2008 in Richmond. Monthly water temperature data was from National Oceanographic Data Center of NOAA (www.nodc.noaa.gov/dsdt/cwtg/satl.html). Monthly water discharge data was averaged from daily stream flow data during the period between 1/1/1984 and 12/31/1996 from USGS gage station 01661800 located in the headwater of Great Wicomico River, VA. Environmental variables were graphically displayed in relation to temporal principal components to visually assess their relationships.

IV-3.7 Relationship between environmental variables and FC contamination

Fifteen variables (comparing to 14 variables in section IV-3.5, impervious surface percentage was added here) were chosen based on their likelihood of association with FC contamination levels in Virginia coastal upstream watersheds. It was assumed that not all the variables contribute equally to FC contamination levels. It was necessary to put weights on variables as an indicator of their contribution. Classification and Regression Tree (CART) analysis helped to address the problem. CART is a non-parametric technique that can recursively partition data into mutually exclusive

groups by selecting a predictor variable that best explains variation in the response variable (Urban, 2002). Statistical software, called JMP 8, was used to perform a CART analysis. The CART model was built for the response variable (FC contamination levels) with 15 predictor variables in 165 upstream watersheds (Table IV- 3.7.1). FC contamination levels were represented by FC geometric mean. FC data were extracted from DSS FC sampling data between 1990 and 1994. The fifteen variables were impervious surface percentage, soil condition, slope, drainage density, eccentricity, residence time, watershed area, water area, water volume, wetland percentage, cropland percentage, pasture percentage, forest percentage, developed percentage, and ratio of watershed area to surface water area. Land cover came from the NLCD 1992 land cover dataset. Prior to the CART analysis, the minimum number of observations permitted within terminal groups was set at 5 and cross-validation was conducted by randomly dividing data into 10 equal size groups.

IV-4 Results

IV-4.1 Tidal and seasonal effects

There were 392 stations that had tidal information and FC concentration data in the study area (Figure IV-4.1.1). The available sample size for a 1-sample Wilcoxon signed-rank test was 2310 (FC data from 392 stations for available months). The result from this test indicated that the FC geometric mean concentration was significantly greater at low tide than at high tide ($n=2310$, $p<0.001$). The difference between the low and high tide median FC concentration values is about 1.92 MPN/100ml with a 95% confidence interval between 1.43 and 2.46 MPN/100ml. The result from seasonal comparisons show that FC geometric mean concentration in summer ($n=614$) is significantly greater than the concentration in winter ($n=596$) ($p<0.001$). The difference in FC levels due to seasonal

and tidal effect is evident when examining boxplots of data distribution (Figure IV-4.1.2). Comparing the seasonal difference between winter (January to March) and summer (July to September), (Q1: 7.31 MPN/100ml, median: 18.04 MPN/100ml, Q3: 41.76 MPN/100ml), to the tidal difference, (Q1: -1.17 MPN/100ml, median: 0.17 MPN/100ml, Q3: 7.05 MPN/100ml), the difference caused by tide is much smaller than the difference caused by seasons

IV-4.2 Re-define study sites in Virginia coastal regions

Three classes of high, middle, and low fecal contamination could be divided by using EOF method. The first spatial component or first temporal component, which contains the largest data variation while reducing the dimensionality of the data, explains about 76% of the data variation. From Figure IV-4.2.1, we can see that the highest FC contamination across months (indicated by the brightest red color) appear in most upstream regions. The contamination (and representative color) decreases in the downstream direction. In order to show more clearly how FC distributes spatially along the waters, the DSS stations were evenly separated into 3 groups according to their first spatial component values, as shown in Figure IV-4.2.2. The first group is the stations which show the greatest spatial component values, second group having second greatest spatial component values, and the third one with the lowest values. It is interesting to see that almost every river branch follows the same pattern with high first spatial component values appearing in the upstream waters represented by the red color. These values decrease moving toward downstream, turning into yellow in the middle stream and then green color in downstream. The first spatial component suggests that in the embayment close to land, there is very high FC concentration variation across different months. In segments closer and closer to the river mouth, the variation in FC concentration loses strength and becomes weaker and weaker across the months. Positive values in PC1

indicate that the spatial pattern shown by the first spatial component is quite consistent through different months. This spatial pattern is more obvious in the warm season than in the cold season. Since the separation into three groups seems to divide most of the water ways similarly into upstream, middle and downstream regions, that is how stations were categorized for subsequent analysis. At same time, watersheds associated with each region were also delineated into upstream watersheds, middle, and downstream watersheds. Only upstream watersheds were actually used for study purposes. Upstream watersheds were delineated using the contour lines on digital 7.5 minute USGS topographic maps for the Virginia coastal region. The contour interval is 10 feet. Streamlines and contour lines were used to determine overland water flows through each basin. The boundaries of the upstream watersheds were assigned to the location between upstream and middle stream water quality stations.

Cumulative frequency graphs were drawn for upstream, midstream, and downstream stations using Minitab 5.1. Figure IV-4.2.3 shows FC frequency distributions among upstream (n= 96047), middle stream (n=100064) and downstream (n=97770). There are much higher FC concentration values in the upstream than in the downstream. Highest FC concentrations appear most frequently in upstream regions, less frequently occurring in the middle stream regions, and lowest in downstream.

There are a total of 187 upstream watersheds delineated as shown in Figure IV-4.2.4. The sizes of upstream watersheds range from 167,102 m2 to 173,718,943 m2 with a mean of 17,933,206 m2 (Table IV-4.2.1). The average number of DSS water quality monitoring stations in their receiving waters is 3 with the standard deviation of 2 (Table IV-4.2.1).

IV-4.3 FC distribution among different land cover dominated watersheds

There are 5 watersheds representing Crop-Pasture dominated watersheds, 4 for Forest dominated, and 5 for Urban dominated watersheds (Table IV-4.3.1 and Figure IV-4.3.1). Most Crop-Pasture dominated watersheds were located on Virginia's Eastern Shore. Forest dominated watersheds were located in the northern part of Virginia"s coastal regions, and Urban dominated watershed were found in the southern portion. Table IV-4.3.1 shows their land cover distributions, related water quality monitoring stations, and the number of available FC data for each station from 1990 to 1994. Results from the K-S test indicated that each pair of FC data between crop-pasture dominated watersheds, forest, and urban dominated watersheds was significantly different from the others, even though green (indicating forest dominated watersheds) and yellow (indicating cropland and pastureland dominated watersheds) curves almost overlapped. The result suggested that fecal contamination levels respond differently between urban dominated, forest dominated and crop-pastureland dominated watersheds. The highest FC concentrations appear most frequently in Urban dominated regions, followed by Crop-Pastureland, and with the lowest occurring in Forest dominated regions (Figure IV-4.3.2). The FC frequency distribution curve for Crop-Pastureland is quite similar to the curve of Forest dominated. The probability of exceeding a given FC levels is higher in urban-dominated upstream watersheds than in forest-dominated upstream watersheds in almost every month as shown in Figure IV-4.3.3. FC distribution in three groups of single land cover dominated watersheds were significantly different from each other with corresponding low p values ($p < 0.001$ in all pairs of K-S test) and greater D values than each of their critical values. D value between forest-dominated and crop-pastureland dominated watersheds is 0.16, which is greater than their critical value 0.11. D value between forest-dominated and urban dominated watersheds is 0.38, which is much greater than

their critical value 0.087. D value between urban-dominated and crop-pastureland dominated watersheds is 0.36, which is also much greater than their critical value 0.088.

IV-4.4 The effects of impervious land surface on fecal contamination

The impervious surface percentage in 1990 and 2000 (Table IV-4.4.1) in 187 upstream watersheds was related to FC contamination levels based on the subset of FC sampling data characterized by rain occurring within 4 days before the sampling date. In 1990, there is at least 96.8% cumulative probability that a detectable change in the FC geometric mean concentration occurs in upstream watersheds with impervious cover percentage at or below 13.78%. Above the impervious surface threshold value, FC geometric mean increased from 22.08 to 37.94 MPN/100ml. In 2000, there is at least 83.5% cumulative probability that a detectable change in the FC geometric mean concentration occurs in upstream watersheds with impervious cover percentage at or below 17.39%. Above the imperious surface threshold value, FC geometric mean increased from 24.67 MPN/100ml to 44.78 MPN/100ml. The probabilities of Type I error were quite low ($p = 0.0008$, and $p = 0.002$). Low p values indicate that there is a strong probability that the derived potential changepoint is real and could represent significant change in fecal contamination levels.

IV-4.5 FC distribution in different river regions

FC concentrations in excess of 200 MPN/100ml (swimming water quality standard) predominately ranged between 210MPN/100ml and 1210MPN/100ml (Figure IV-4.5.1). There are two notable outliers (They are thought as outlier because more than 99.9% of FC concentration data are much lower than these two values). One (4600MPN/100ML) occurred in the James River on March 16th, 1989 at station 62_9.1A, which is located in

the mouth of Brewers Creek, on the south side of the James River. Another notable outlier (2440MPN/100ml) occurred on June 28th, 1988 on the south side of Potomac River. Regional differences in FC distribution were revealed by K-S test after removing these two outliers. FC distributions in these five regions were significantly different from each other with corresponding low p values ($p < 0.001$ in all pairs of K-S test) and greater D values than each of their critical values. Sample sizes of each region, their calculated D values, and critical D values are shown in Table IV-4.5.1 and Figure IV-4.5.2. The result showed that the James River region has the greatest FC concentration data range, followed by the York River, the Rappahannock River, the Potomac River, and the Eastern shore region. Median values (23MPN/100ml) were equal in the James River, the York River, the Rappahannock River, and the Potomac River. The Eastern shore showed the lowest median value (15MPN/100ml). There was about 10% of chance of FC concentrations exceeding a value around 200 MPN/100ml.

There are 33 upstream watersheds around the Rappahannock River, 33 upstream watersheds located on the Eastern Shore, 13 around James River, and 28 around York River (Table IV-4.5.2). The Principal Component Analysis of these 107 upstream watersheds showed that the first principal component accounts for 30.2% of the variability and the second component accounts for 21.8% of the variability (cumulatively 52%) (Figure IV-4.5.3). The first component was correlated with a non-urban gradient, with percentage of forest and slope increasing in the negative direction together with percentage of cropland and pastureland increasing in the positive direction as shown in Table IV-4.5.3. Slope, percentage of forest, pasture, and cropland contributed most to this component. Coefficients of these variables showed their correlation with each other. Results suggested that forest was located in areas with relatively steep land surface, indicated by the value of slope (both coefficients are negative values). Cropland and

pastureland occur where the land has a low value of slope (cropland and pasture have a positive coefficient, slope is negative). The second PC seemed to make a quick sketch about what the environment looks like based on the size of the watershed, water area, and water volume. At the same time, it shows an urban gradient with percentage of developed land, watershed area, water area and water volume increasing in the positive direction, and the percentage of forest decreasing in the negative direction. Developed land tends to correlate significantly with water area, drainage density, and less significantly with watershed area and water volume.

Based on Figure IV-4.5.3, the separation of the James River region from others was relatively clear. It seems the Eastern Shore region might possibly be distinguished from other two regions. PCA analysis was conducted on the Rappahannock, York, and the Eastern shore regions (94 watersheds) as shown in Figure IV-4.5.5. The first PC explains 37.4% of data variation, with 20.1% for second PC (cumulatively 57.5%), as shown in Table IV-4.5.4. There is clear separation among these 3 regions as shown in Figure IV-4.5.5, even though the first two PCs only explain 57.5% of data variation. Slope is probably one of the major factors separating the Eastern Shore from the other two regions. The separation between the Rappahannock and York depends largely on runoff potential and the percentage of pastureland.

IV-4.6 Climate effect

The examination of FC level response to annual precipitation reveals a close relationship between FC amount and precipitation intensity from 1985 to 1998 (linear regression with r^2=0.75) (Figure IV-4.6.1). The rise and fall of FC bacteria concentration closely associates with annual precipitation cycles. After grouping rainfall intensity, FC

concentration variation seems to have a positive relationship with grouped rainfall intensity, especially with Day 1 precipitation, as shown in Figure IV-4.6.3.

A general temporal pattern of fecal contamination throughout Virginia coastal regions has been shown in Figure IV-4.6.4. The red lines separate locations into three groups – 1) the Potomac, the Rappahannock, and Mobjack Bay group, 2) the York and the James River group, and 3) the Eastern Shore group. These graphs are all on the same scale. FC concentrations from January to March are quite low across almost all the stations. In February, these concentration values are probably the lowest during the year. Starting in April, FC concentration values increase until October. FC concentrations start to drop in November and are even lower in December.

In order to quantify the influence of several natural forces on fecal contamination levels, the first several temporal components were linked to monthly precipitation, temperature, and water discharge. Based on EOF results, the first spatial component or temporal component explains about 63% of the data variation with second accounting for 12.7% and the third only 5.3% (Figure IV-4.6.5). The first 3 principal components together explain 81% of the data variation. The first principal component was linked to monthly precipitation intensity (Figure IV-4.6.6a). Variability in fecal contamination levels appears to be an upstream-wide response to precipitation. High FC concentration values occur in the wet season with more rainfall, and low values occur in the dry season with less rainfall. The second component was linked to monthly temperature. Figure IV-4.6.6b shows a positive relationship between air, water temperature and FC count, which means that temperatures play a role in the amount of FC measured in the receiving water. And the third component was linked to monthly water discharge (Figure IV-4.6.6c). Fecal contamination levels respond to temperature and flow discharge. These two factors

account for 12.7% and 5.3% of the total variance, respectively. There is about 19% of data variation left unexplained.

IV-4.7. Relationship between environmental variables and FC contamination

Initially there were 15 variables chosen to represent environmental characteristics. The number of potential predictors was reduced to 12 variables after removing 3 variables (water volume, water area, and watershed area), since they closely correlate to each other with Pearson's correlation coefficient greater than 0.6. Pearson's correlation coefficient of the other pairs of variables were all less than 0.6. In order to avoid collinearity (King et al., 2005; Norton 2000), bare land and the area of open water were included in the land cover percentage calculation. So the sum of 5 major land cover percentages (not including bare land and the area of open water) won't equal to 1. The median of FC abundance in these watersheds is 23.2MPN/100ml (Q1 = 17.1 MPN/100ml and Q3= 28.9 MPN/100ml). Based on the minimum value from cross-validation, 7 splits were determined from CART analysis (Table IV-4.7.1. The complete tree explains a total of 42.7% of FC abundance variation. This variation was explained by Impervious surface percentage (r^2=4.3%), Forest(r^2=4.7%), Pasture(r^2=3.5%), and Wetland percentage(r^2=8.2%), ratio of watershed area divided by water area(r^2=7%), residence time(r^2=8%), and runoff potential(r^2=7.4%) (Figure IV-4.7.2). FC concentrations were highest in 13 watersheds that met the following conditions at the same time: 1. watershed:water area ratio value is less than 76.35; 2. runoff potential is greater than 0.034; 3. impervious surface percentage is greater than 0.6%; 4. wetland area is greater than 5%; and 5. residence time is longer than 0.6 day. The second highest FC concentration occurred in 20 watersheds with ratio values greater than 76.35. FC concentrations were lowest at 7 watersheds with ratio values less than 76.35, runoff

potential smaller than 0.034 and forest occupying more than 49% of the whole watershed. The remaining watersheds were classified into 5 groups with similar FC concentration values.

IV-5 Discussion

IV-5.1 Tidal and seasonal effects

One of the principal physical forcing mechanisms affecting the water quality in Virginia coastal waters is tidal variation. Monthly comparison of the tidal effects on the FC geometric mean concentration was done in order to separate bacteria loading differences induced by tidal influences from those induced by seasonal influences. The result indicates that FC geometric mean concentration is greater at low tide than at high tide. This is consistent with the previous study by Mallin et al. (1999), which observed the increase in the abundance of FC bacteria in tidal creek waters at or near low tide. Since Virginia coastal waters are located in the lower part of Chesapeake Bay, no tidal oscillation inside Chesapeake Bay will ever be free from the tidal 'hammer' perpetually at work at its entrance (Boon, 2004). Boon (2004) also mentioned that, of the four major tributaries in Chesapeake Bay, one is relatively short (i.e., the York River) and displays a uniform increase in tidal range upstream, while the longer ones (the James, the Rappahannock, and the Potomac Rivers) show a slight decrease in range before the final increase upstream. The tidal range at the head of all four tributaries approaches the range at the bay entrance itself (90 cm). Tidal ranges in Virginia coastal water area varies from 0.6 – 1.0 m. Factors contributing to the greater FC geometric mean concentration at low tides could be the salinity variation between high and low tide, increasing turbidity during low tide disturbing FC bacteria into water column, and dilution effect during flood and ebb (Mallin et al., 1999).

One of the objectives of this study was to quantify FC sources with an inverse modeling approach. Because increasing the number of independent variables being modeled could promote the development of a widely varying (chaotic) solution (Nihoul, 1998), limiting the number of independent variables is a critical decision to make before designing a successful water quality model. The results of the preceding analyses suggest FC concentration differences due to season are greater than the differences between high and low tide. It is therefore better to consider seasonal effect prior to the tidal effect. The quantification process could be separated into two periods – cold and warm when considering seasonal effects. Given monthly FC data, it is not feasible to quantify FC sources during either flood or ebb period.

IV-5.2 Re-define study sites in Virginia coastal regions

Although causal factors of FC contamination have been identified by numerous research studies (Mallin et al., 2000; Kim, 2005; Line et al., 2008) their inter-connection or interaction limits the ability to clearly differentiate the effects of specific attributes of land and water on fecal pollution. The capability of predicting the levels of contamination is low as well. In this study, the separation into upstream, middle and downstream reaches helped differentiate factor effects, especially from water-based processes such as salinity, tidal flushing and dilution. Most of the analysis focused on upstream land and water, because upstream water quality reflects the concentrated effect from land. In addition, FC monitoring data in middle and downstream reaches alone couldn't provide sufficient information to compare watersheds. This is because the effect of local pollution sources on in-stream water quality cannot be separated from the effects of contaminants originating in upstream watersheds (Smith, et al., 1997).

Results from FC distribution comparison of upstream, middle and downstream suggested that the probability for FC concentrations to exceed a given bacteria level increased significantly from downstream, up to the headwater region (Figure IV-4.2.3). Highest FC concentrations mostly occurred in upstream regions, where salinities are low and there are relatively larger FC contributing land areas compared to middle and downstream. Lowest FC contamination levels occur in downstream regions, which experience high salinity, accompanied by greater tidal flushing and dilution processes. Many studies have demonstrated that there is a negative relationship between FC bacteria survival and salinity (Hanes and Fragala, 1967; Evison, 1988; Solic and Krstulovic, 1992). Downstream stations also have wider and deeper water, less local contribution, and are further from FC sources as opposed to upstream reaches (Burkhardt et al., 2000). Fecal bacteria decay rates are directly related to the distance from the sources. However, since water quality reflects the land characteristics that are drained, it is hard to definitely conclude that dominant reason for FC contamination gradient along river is from water-based processes, such as salinity, tidal flushing and dilution, or from land-based processes. The conclusions made by other papers based on single observations seem to lack sufficiently supportive evidence (Goyal et al., 1977; Esham, 1994; Mallin et al., 2000).

This study demonstrated that there was a consistent spatial pattern in almost every embayment, with high spatial component values upstream, decreasing when moving downstream. This consistency suggests that some processes exist either in land or water, which occur relatively ubiquitously. The variation in land parameters is relatively greater than the variation occurring in water parameters such as salinity, dilution, and tidal influence from headwater to the mouth. The consistent spatial pattern infers that FC

distribution difference between upstream, middle and downstream can be mostly attributed to the gradient of salinity, dilution, and tidal influence instead of land-based activities.

IV-5.3 FC distribution among different land cover dominated watersheds

Most watershed models use land cover or impervious land condition as one of the input variables (O'Neill, et al., 1997). Land cover refers to physical or biological features on the land surface. In general, there are 6 major types of land cover – Forest, Cropland, Pastureland, Urban, Wetland and Water. Each land cover has its own specific characteristics. For example, forest has many standing trees, pervious soils with low erodibility, and habitat for wild animals. In this studied area, slope is more closely correlated to forest land (Pearson correlation coefficient 0.47, $p < 0.001$) than any other type of land cover (Urban: -0.147, p=0.072; Cropland: -0.288, $p < 0.001$; Pastureland: -0.136, p=0.095). So each land cover represents the sum of effects from lands, which include the effects from slope, soil properties, vegetation cover, etc. Their total effects may be reflected in the water quality responses within the upstream embayment. FC contamination responds differently between urban-dominated and forest-dominated upstream watersheds, which probably mirror the differences between these two contrasting land covers.

It must be emphasized that frequency comparison only focused on the type of land cover in a watershed. It didn't incorporate any specific information about other variables, like slope, runoff potential and so on. However, there was a difference between two of the frequency curves (Figure IV-4.3.2). It is not surprising that embayments in urban-dominated upstream watersheds pose a higher risk for human health exposure to

pathogens, indicated by the amount of FC bacteria. It has been suggested that impervious surfaces in urban area increase the transport of bacteria to water, heightening contamination. Many studies have been trying to reduce the negative impact from urban development on pollution issues (Maiolo and Tschetter, 1981; Kocasoy, 1995). As suggested by Mallin et al. (2001), direct discharge of stormwater runoff from urban area to coastal waters should be prevented. One management alternative is to redirect stormwater via leaching structures to the groundwater pathway, where FC transport could be limited. Rain barrels are recommended by EPA to reduce stormwater runoff. Citizens have been encouraged to install rain barrels under their roofs to collect rainwater in order to hold back the pollutants, which are otherwise washed off from land surfaces into receiving waters.

Many experimental designs have demonstrated that vegetated surfaces may ameliorate the degree of fecal pollution (Tufford and Marshall, 2002; Roodsari et al., 2005). What makes forest-dominated upstream watersheds different from urban ones maybe be attributed to runoff volume during rainfall events. Research data suggest that for rainfall events of similar magnitude, the volume of runoff was 3–25 times greater in the receiving waters of developed watersheds in South Carolina than in forested watersheds (Holland et al., 2004). The large difference between runoff volumes is likely a major reason for the differences in the FC bacteria probability distribution between urban and forested-dominated upstream watersheds, since the transport of microbes into water systems often occurs through sediments in surface runoff (Reddy et al., 1981). Even though forest-dominated embayment showed lower fecal contamination levels, forest is still considered a source for FC bacteria from land. Elevated FC concentrations have been detected from streams and spring located in national forest parks (Silsbee and Larson, 1982; Becker, 2006). The numbers of visitors, as well as the FC bacteria existing in soil,

leaf litter, and stream sediments from natural sources, appear to be the major contributors to bacterial contamination. The more remote an area is from human and animal pollution, the less likely are fecal types to be found (Geldreich et al., 1962). Forest-dominated upstream watersheds in this study might be remote from human pollution, but definitely are not remote from animal pollution.

Urban and forest-dominated upstream watersheds were compared with watersheds dominated by cropland-pastureland (Figure IV-4.3.2). One of the reasons to combine cropland and pastureland together is the percentage of these two kinds of land cover correlate quite well with each other (Figure IV-5.3.1).

Figure IV-5.3.2 shows that the median value (15MPN/100ml) for Cropland-Pasture is lower than forest (23MPN/100ml). The result seems contradictory to the idea that cropland is a major source of fecal bacteria from land. The EPA's National Water Quality Inventory report (USEPA, 2000) identified bacteria from cropland as the leading cause of impairments in rivers and streams in the United States and agricultural practices were identified as the leading source of all bacterial impairments. It has been well-documented that runoff from cropland, as well as livestock and poultry litter-applied areas, is a source of fecal contamination in water (Edwards et al., 1994, 2000; Crowther et al., 2002; Tian et al., 2002; Gerba and Smith, 2005).

As a livestock and poultry litter-applied area, pastureland has been identified as a source of fecal bacteria (Soupir et al., 2006). Pinney and Barten (1997) mentioned that manure is collected and spread on pastureland. However, pastureland soil probably contains less fecal bacteria than cropland soil. Geldreich et al. (1962) examined coli-aerogenes bacteria that was isolated from 251 soil samples collected from 26 states and 3 countries. Their

results suggested that the percentile distribution of MPN values/g in Pasture soil is much lower than Cropland soil. FC concentrations in soil are an important parameter determining the potential for contamination of water resources. The greater the concentration, the more likely some will be transported (Goss et al., 2002). It is therefore the combination of cropland with pastureland could underestimate cropland contribution to fecal contamination in their receiving water.

IV-5.4 The effects of impervious land surface on fecal contamination

The quantity of impervious cover is useful to measure changes in development and reflect the gradients of human influence. In 1990, there were only 10% of upstream watersheds in which impervious cover occupied more than 5% of all land cover. After 10 years, the number of upstream watersheds with more than 5% of land as impervious cover increased to 15%. Land conversion from rural to urban and suburban has proceeded rapidly along coastal watersheds due to increasing human population in coastal areas. Mallin et al. (2000) pointed out that the percentage of impervious surface area alone could explain 95% of the variability in average estuarine FC abundance for five estuarine watersheds (Figure IV-5.4.1). Even though it emphasizes the relationship between impervious surface area and FC abundance, five data points alone may not provide sufficient information to demonstrate a comprehensive relationship.

Results from Nonparametric Changepoint Analysis showed that the potential impervious cover threshold values were 13.78% in 1990 and 17.39% in 2000 (Figure IV-4.4.1) . This indicates that there is significant change in fecal contamination levels when impervious cover percentages exceed around 15%. The result is similar to previous research. Based on a variety of studies, when more than ten percent of the acreage of a watershed is covered in roads, parking lots, rooftops, and other impervious surfaces, the rivers and

streams within the watershed become seriously degraded (Schueler and Holland, 2000,). The principle of the ten percent impervious threshold has been brought up as important consideration for marine ecosystem protection programs. Even with fiscal, social, and environmental unsustainability as consequences, hypersprawl, that is housing at densities of no more than one unit per three acres, is encouraged by current environmental policies as a solution to nonpoint source pollution (Beach, 2002). Mallin (2002) suggested that in a watershed with urban land exceeding 10 percent, surface runoff should be directed into natural or artificial wetlands, grassy swales, and other porous areas before surface water runoff can enter coastal receiving waters.

King and Richardson (2003) mentioned that one potential criticism of nonparametric changepoint analysis is that it may not detect a low-level changepoint if a second, competing changepoint occurs at a higher concentration. They suggested splitting data into multiple subsets. This was not attempted in the present study because there are only a few data points with high impervious cover percentage in each of the two data sets (7 data points with impervious cover >15% in 1990, 8 data points with impervious cover >17% in 2000). Data splitting would be quite arbitrary and the lack of data points at higher levels of imperviousness would confound the purpose of the analysis. Even though several studies have identified thresholds for development impacts on water uses, none of studies has identified the threshold values from such large dataset, especially for the coastal area in Virginia.

IV-5.5 FC distribution in different river regions

IV-5.5.1 Data discussion in different regions

In general, 90% of the FC data in the study regions were less than 200 MPN/100ml. The magnitude of high FC concentration values (any values greater than 200MPN/100ml, a

water quality standard for safe swimming) in the study area was between 210MPN /100ml and 1210MPN/100ml. One outlier occurred in the mouth of Brewers Creek, on the Southside of the James River. Daily precipitation records at Norfolk International Airport from the NOAA web database showed that there was a large amount of rainfall during the previous 3 days. The observation is consistent with previous research that FC concentrations increased significantly with increasing rainfall occurring in the days before sample collection due to storm runoff (Lipp et al., 2000; Sullivan, 2004). The high FC concentration at station 62_9.1A may be attributed to boating activity. The data from the DSS survey shows there are some boating activities close to the sample station. Pettibone et al. (1996) observed that the levels of FC increased immediately after a ship passed. An et al. (2002) mentioned that recreational boating activity in lake marinas may have resuspended bottom sediments with bound *E. coli*, and the presence of *E. coli* in marinas was not an indication of recent fecal contamination.

Another notable outlier (2440MPN /100ml) occurred on June 28th, 1988. After checking related information, it was found to be similar to the other outlier. Rainfall on June 27th was recorded in the DSS database as 0.66 inches and there were boating activities nearby.

Regional differences in FC distribution were revealed in part through examination of FC data distribution patterns (Figure IV-4.5.1b). A comparison of their medians was not sufficient to distinguish regions. Box plots, together with histograms or frequency distributions in cumulative curve, help in this regard, and are important statistical methods in exploratory data analysis. A useful comparison is between the FC concentration cumulative frequency distribution plot in different regions (Figure IV-4.5.2) and the daily rainfall cumulative frequency distribution in 1998 and 1999 obtained from Norfolk International Airport NOAA web database (Figure IV-5.5.1). The two frequency

distributions exhibit a similar shape. The FC frequency graph showed there is about 10% of chance for FC concentrations to exceed the value around 200 MPN/100ml. On the daily rainfall graph, when rainfall intensity is greater than about 0.5 inch/day, the curve coincidently flattens with a percentage around 90%. That is, the frequency of FC distribution matches quite well with the frequency of precipitation that occurred in Virginia coastal areas. The comparison provides additional support that precipitation is an important driving force for FC bacteria transport from land into water, as proposed in previous researches (Sullivan, 2004). The results might imply that there is at least a 10% chance of exceeding the swimming standard. This 10% seems to be unrelated to human activities, , resulting instead from natural forces.

The characteristics of FC distribution within the river regions were different from each other as shown in Figure IV-4.5.2. The probability of having high FC concentration values is greatest in The James River region. The Eastern Shore has a large amount of low FC concentration values compared to other regions, while it has a slightly greater percentage of high values than the Rappahannock and the Potomac. There is probably no distinction between the Rappahannock River and the Potomac River, which have the lowest percentage of high concentration values. The York River lies between these curves. One interesting observation here is that since The Eastern Shore has a greater percentage of low concentration values than the Rappahannock and the Potomac River, you would expect that the Eastern Shore should have relatively lower percentage of high values than the other two river regions. But this is not the case even though the probability of high values in The Eastern Shore is only slightly higher than the other two.

IV-5.5.2 Regional Environmental Characteristics

Although FC concentrations provide important information on the local (onsite) pollution levels, data alone give little indication of how the system generates the amount of fecal bacteria in the water. For instance, FC concentration may be low or moderate in the water that receives high fecal material input because the bacteria is quickly diluted and flushed out. On the other hand, FC concentrations may be high in water that receives low to medium input, possibly because land surface conditions, either impervious or steep, provide a quick way to drive bacteria into the water without experiencing huge losses during land transport. Successful management requires a variety of information, including the knowledge of environmental and physical settings, such as land cover combinations, soil type, climatic setting, and topography.

Even though fourteen variables were selected to represent environmental characteristics, they still provide an incomplete description of the surrounding land's influence on fecal pollution. For example, the analysis did not include reservoirs, lakes, retention pond or detention ponds, which probably have an effect. In addition, the effects of land fragmentation, roads, population density, exposure to ultraviolet radiation, sediment resuspension, and other phenomena were not considered, although they have important consequences for fecal pollution (Cook, 1984; O' Neill, et al., 1997; Mallin et al., 2000;). For this analysis, direct measurements of land and water characteristics were the focus. In addition, the analysis was confined to the upstream watersheds, not the middle or downstream regions.

The separation of the James River from other regions is apparent when the scores of each watershed were plotted from the first two principal components (Figure IV-4.5.3). The James River upstream watersheds are characterized as having a high percentage of

developed lands with large watershed areas, water areas, as well as large amounts of water indicated by water volume. Many of the hydrologic impacts on streams are the result of development, represented by impervious areas in urban and suburban areas. There was no clear distinctions between the Rappahannock, the York, and the Eastern Shore (Figure IV-4.5.3), even though K-S test showed significant differences. Therefore, a secondary PCA analysis was conducted on these 3 regions (94 watersheds) as shown in Figure IV-4.5.4. The first PC explains 47% of data variation, with 12.6% for the second PC (cumulatively 59.6%). There is a clear separation between the 3 regions (Figure IV-4.5.4) even though the first two PCs only explain 59.6% of data variation. Slope is probably one of the major factors separating the Eastern Shore from the other two regions. The Eastern Shore upstream watersheds also are characterized by relatively higher percentage of land as cropland and smaller size of watershed area. The area of Eastern Shore is very flat according to Digital Elevation Models (DEMs) by USGS The area was dominated by cotton, soybean, vegetable and truck farming, and large-scale chicken farms. The separation between The Rappahannock and York depends largely on runoff potential and the percentage of pastureland. The Rappahannock study area has more percentage of land as pastureland than York, but soil in the Rappahannock studied area has less runoff potential than in York. Since there are no studies exactly analyzing runoff potential in the same locations as my study areas, sediment yields from two rivers were used as a reference. Studies have shown that the Rappahannock River delivers more sediment per square unit of watershed than any of the other tributaries of the Chesapeake Bay (USGS, 2003). However, these study areas for regional comparison are only located in upstream watersheds of lower the Rappahannock River and the York River. The York River study indicated that little sediment from the watersheds located in upper York River reached the estuary and water quality may be more affected by locally derived sediments near the estuary (Herman, 2001). According to USGS report, we can probably

infer that the lower York River has the possibility to deliver more sediment per square unit of watershed than the Rappahannock, since sediment source in the York river might be concentrated in the places near the estuary mouth.

IV-5.3.3 Correlation between FC contamination and environmental characteristics

Based on analyses discussed above, FC concentration distribution reflects environmental characteristics of different regions. The highest FC concentration range occurs in the James River, as well as the highest incidence of sampled data having elevated FC concentrations, probably due to the high percentage of developed land. Many studies have shown a strong correlation between urbanization and declining water quality. It is not surprising that the upstream watersheds in the lower James River had the worst contamination levels compared to the other regions. For other associated variables, like the size of land and water, they indicate that FC contamination in the James River reach further downstream than other regions because of the way the embayment was separated into upstream, middle and downstream. The lines to divide the water into upstream and middle stream in all embayment represent reaches where FC contamination exhibits similar levels. For areas with the worst case, the line would extend further downstream and the size of watershed and water would increase simultaneously if water-based processes, such as water dilution, are not strong enough to push the line back toward headwaters. Therefore the size of land and water in part reflect FC contamination levels in all study areas.

The lowest FC concentration median values occur in the Eastern Shore which has a large percentage of low FC concentration values, a small percentage of medium values, and a relatively larger percentage of high values as compared to the Rappahannock and the Potomac. This pattern probably is attributable to the environmental variables of the

Eastern Shore, characterized as a flat area with small slope values and intensive agricultural operations. Although the Eastern Shore comprises only about 5% of the total Bay watershed, it contains the most concentrated grain and poultry producing regions in the entire watershed (Staver and Brinsfield, 2001). The ratio of agricultural land to forest on the Eastern shore is approximately 1:1 versus 1:2 for the entire bay watershed. Huge amounts of manure that are applied in a concentrated time period probably contribute to the larger percentage of high FC concentration values compared to the Rappahannock and the York River. Flat land surface in the Eastern Shore is conducive to water infiltration which probably transfers surface water into groundwater. Reay (2004) examined several sites, including ones in Cherrystone Inlet, which is a small tidal tributary located on the Eastern shore, and found that FC concentrations were at or near background levels in groundwater immediately adjacent to a waste water drain field and along the shoreline. In addition, the study sites generally had a shallow water table and permeable sandy substrates, which represent a high risk setting for groundwater contamination from domestic wastewater disposal. Flat topography and special soil purification capability probably can explain low FC contamination levels in the Eastern Shore. Comparison between the York and the Rappahannock River, indicates the probability to exceed a given FC concentration values is greater in the York than the Rappahannock. Percentage of pastureland and soil runoff potential probably distinguishes the York from the Rappahannock. Spatial variability of hydrologic soil groups, as well as land cover, results in spatial variability of runoff within a watershed (Figure IV-4.5.4). Soil hydrologic characteristics contrasted between the two regions (Figure IV-5.5.3). The study area in the Rappahannock contains more soils with moderately low (B) runoff potential, while the York contains more soils with moderate and high runoff potential. The standard deviations for all hydrologic soil groups were generally high, which reflected the high variation of runoff potential in each region. Soils may contribute large

amounts of bacteria to drainage water since they abound with lots of bacteria (Geldreich et al., 1962). Thus the York upstream studied watersheds may have a higher possibility of exceeding water quality standards for shellfish harvesting than the Rappahannock, if both of them have similar environmental settings except for their soil runoff potential.

IV-5.6 Climate effects

Although the hydrodynamic phenomenon is generally independent of the water quality component, water quality depends on the hydrologic transport process (NRC, 2000). The association between FC levels and annual precipitation suggests that FC source loadings are potentially consistent with rainfall events. Pollutants existing on the land surface would build up on the land between rain events and be washed off by subsequent rain events. Average FC levels in the receiving water may be determined by the quantity of water running over the land. As the rainwater passed over land surfaces, anything on the land surface, which could be carried away, would be entrained and flow together into the adjacent waters. As rainwater increases, combined sewer overflow would release a combination of diluted sewage and storm water into the rivers when the interceptors are unable to transport the extra volume of water to the treatment plant (3RWWDP, 1998). Both processes would increase the amount of fecal bacteria in the water.

Annual precipitation correlates well with FC mean concentration values (Figure IV-4.6.1). A good correlation was expected between FC concentration and precipitation occurring 7 days before sampling dates, since a previous study showed that there is a significant correlation between FC concentrations and rain during the 24 h prior to the day of sample collection ($r = 0.601$, $p < 0.0001$) (Mallin et al., 2001). However, when scaled down from the annual temporal cycle to daily rainfall data, the strong association turns into a weak

correlation, even though it shows positive relationship between FC concentration and grouped rainfall intensity. Grouping rainfall intensity is because the FC data didn't follow a continuous distribution within the range of rainfall intensity. It might expose the weakness of FC MPN measurement. Or the amount of FC bacteria has nonlinear relationship with rainfall intensity and the linear regression might not show clear FC abundance response to the precipitation. It might exist threshold values for FC abundance to reach when the rainfall intensity exceeds certain amount. Also the weakened relationship could be due to that the analysis on the prior rainfall condition relies heavily on local rainfall variation. The inaccuracy of local rainfall data is probably one of the reasons for this poor correlation. Another possible reason is that most studies focus on the rainfall intensity and few of them pay attention to rainfall duration. Mentioned by Hunter et al. (1992), as rain continues, an increased rate of bacteria removal from land depleted the land storage of bacteria sufficiently for a dilution in the FC concentration in the receiving water to occur. The result might also suggest that when looking at the fecal contamination issues from smaller temporal scales, site-specific information such as land cover, slope, soil condition, and other variables cannot be neglected. Key factors with significant impacts on fecal contamination issues include sediment resuspension, salinity, temperature, nutrient availability, growth and mortality, distance to water, boat activity, and wind (Anderson et al., 1979; Struck, 1988; Pettibone et al., 1996; Edwards et al., 2000). It is important to have site assessments to help understand these factors and their contributions in a complex watershed.

In addition to the natural factors (i.e. precipitation), key temporal factors with significant impacts on FC contamination also include temperature variations, water discharge, wind, and tides. However, beyond the general understanding of rainfall, temperature, and other factors' influence on fecal pollution, there is little guidance in the literature as to what

degree fecal contamination levels are determined by these natural forces. This study attempted to quantify the influences of several natural forces on fecal contamination levels.

One way to examine the temporal variability of fecal contamination levels is to analyze all the FC water quality monitoring stations individually throughout Virginia coastal waters. It is obviously a time-consuming and tedious task. EOF method was applied to easily extract temporal principal components, which represent trends, seasonality, or regular fluctuations using all observed data points. In this study, time series were based on monthly observations, but only for one-year periods. One reason for this is due to the monthly data collection and missing data. It is unlikely that one observed value in a month could represent the FC contamination levels for that month. The second reason is that in most cases, water quality monitoring stations for an entire watershed will be sampled in the same day. The data show that, once a missing data value is encountered, it is often the case that all the values from that watershed are missing. Therefore those monthly FC geometric mean concentrations were calculated for each station from all available data to represent the fecal contamination levels for each month. An inevitable outcome for doing this is that the data variation has been reduced before applying the EOF method.

Even though there are some shortcomings to applying the EOF method, the results are still informative. Postulating physical or environmental characteristics that may be correlated with principal components allow for further interpretation of observed patterns. The first temporal principal component shows a similar pattern with the general temporal pattern for all the sampling stations (Figure IV-4.6.4), with high FC concentration values occurring in the warm season, low values in the cold season. Previous studies have shown

similar results with high FC counts in summer, but low FC counts in winter (Novotny and Olen, 1994; Lipp et al., 2001; Line et al., 2008).

A close association between precipitation and FC levels can be easily identified (Figure IV-4.6.6a). This relationship has been examined and discussed in many different ways in the literature review (Lipp et al., 2001) and previous sections. Even though the rainfall 7 days before sampling date has a weak correlation with the FC levels, annual precipitation can explain almost 75% of the annual FC concentration variation in the studied Virginia coastal waters. Mallin et al. (2001) found that there was a significant correlation between FC counts and the amount of rainfall during the 24 h prior to the day of sample collection ($r = 0.601$, $p < 0.0001$). Even though there is quite close relationship suggested by Figure IV-4.6.6a, it is still possible that PC1 could relate to a combination of precipitation, temperature, or other factors.

There was a positive relationship between temperature and FC counts suggested by Figure IV-4.6.6b. The result suggests temperature is an important factor determining FC bacteria survival rate, with warm temperatures favoring survival more than cold temperature. Previous investigations have found that temperature has both direct and indirect effects on bacteria survival, with both positive and negative consequences. Bacterial densities at elevated temperatures were the net result of multiplication (during the initial 3 days) and predation-antagonism and death (Rhodes and Kator, 1988). Bacteria sublethal stress and mortality in filtered estuarine water are inversely related to temperature (Anderson et al., 1979; Rhodes et al., 1983). This means enteric bacteria would be expected to have increased survival rates in warm water. However, bacterial predators also flourish in warmer waters, and grazing by microheterotrophic flagellates controls bacterial numbers in coastal waters (Anderson and Fenchel, 1985). Studies by

Rhodes and Kator (1988) demonstrated that, although pronounced multiplication of enteric bacteria occurs at warmer temperatures, the net effect of increased temperature in non-filtered estuarine water was *E. coli* removal. FC in stabilization ponds effluent discharge showed similar pattern with *E coli*, that is longer survival in winter than in summer (Legendre et al., 1984; Monfort and Baleux, 1991). Even though there are some controversies in previous research, the results suggest that in warmer conditions less sub-lethal stress and low mortality of FC bacteria more likely offset increased predation. On Figure IV-4.6.6b, both lines don't match quite well, with temperature peaking on July and August, but the second temporal component (PC2) peaking on September. One explanation is that the response of FC amount to the temperature was delayed due to the net result of multiplication, predation, and death. Another explanation is that temperature is probably not a good variable to be chosen. The alternated variable might be the frequency and the intensity of tropical hurricane in September. Since tropical hurricane in Virginia occurs frequently in September (Figure IV-5.6.2) (Aiyyer and Thorncroft, 2006).

A weak association between FC concentration and water discharge has been observed in Figure IV-4.6.6c. It seems questionable that FC concentration was greatly influenced by the amount of rain, but much less influenced by water discharge. One possible confounding factor is that water discharge data used in this analysis is from a USGS gage station located in the headwaters of the Great Wicomico River, VA. Compared to the general water discharge in VA, these data show similar patterns (Figure IV-5.6.1). However, the UGSG monitoring network was not designed specifically to assess inputs to coastal regions (NRC, 2000). The NRC committee concluded that "there are major missing pieces in the resultant data set that are needed to support the management of healthy coastal ecosystems; for instance, monitoring sites "below the fall line" (the transition point between lowland and upland portions of rivers, marked by waterfalls and

other rocky stretches that limit navigability) are few and far between." Nevertheless, the quantity of rainwater running on the ground may determine the amount of bacteria mobilized and carried away. This means that a large amount of rainwater may carry more bacteria traveling a longer distance. Once bacteria have been mobilized, they will flow with the confluence of rain water on the land surface, even though the water itself may experience evaporation, infiltration, absorption by plants, or other processes. The initial separation of bacteria from land by rainwater probably leads to the closer relationship to rain intensity rather than the amount of water discharge. This suggests that precipitation is more useful in predicting the FC contamination levels than water discharge values. Hence, an important strategy for reducing FC levels is to mitigate runoff from different land covers before they enter into the waters.

The degree of FC levels is largely determined by the intensity of rainfall and temperature, or their combinations. The mobilization of bacteria from the land by rain water may explain the low contribution of water discharge volume to the degree of fecal contamination levels. Based on the analysis, rainfall, together with temperature and flow discharge, explained about 81% of data variation. These three natural forces cause difficulties in reducing pollutant loads. Because the control of these nature forces is impractical and probably beyond human control, it seems that there is not much opportunity left to really improve environmental condition. However, this study demonstrates the need for exploration and support of innovative approaches to reducing runoff, such as Environmental Site Design. This approach attempts to capture stormwater onsite rather than rushing it away through curbs and gutters.

The percentage of data variation left unexplained (about 19%) in FC temporal patterns could probably be attributed to the effects from wind, tide, boat activity, or other factors

(Anderson et al., 1979; Struck, 1988; Pettibone et al., 1996; Edwards et al., 2000). Despite the limitations of the monthly FC data set available for this study, the analysis provides a baseline that can be built upon with future refinement of data, and the analytical method can be easily applied to other contaminants.

Mallin et al. (2001) speculated that if global warming brings about increased coastal rainfall, this may have a synergistic effect with increased developed land that causes microbial pathogen loadings to coastal waterways to increase in both frequency and concentration. Virginia might experience higher temperature and more frequent rainfall events, accompanied by rising sea levels in the future. A USEPA report (1998) about climate change in Virginia mentioned that, based on projections made by the Intergovernmental Panel on Climate Change and results from the United Kingdom Hadley Centre climate model (HadCM2), by the year 2100 temperatures could increase by 3° F in winter, spring, and summer (with a range of 1-6° F) and 4°F in fall (with a range of 2-8° F). Precipitation is estimated to increase by 20% in all seasons (with a range of 10-30%). In Newport News, sea level already is rising by 12 inches per century, and it is likely to rise another 23.3 inches by 2100. Changing temperature and rainfall patterns, as well as rising sea levels, may contribute to greater fecal contamination variation both spatially and temporally in Virginia coastal regions.

I) Spatial influence on fecal contamination from climate change:

i) With increasing rainfall events, freshwater flow would strengthen estuarine circulation and change the salinity regime. It could move freshwater further downstream if the rainfall event was strong enough and high FC concentration values would be expected to occur more frequently in the downstream regions. This might lead to larger closure zones for safe swimming and shellfish harvesting.

ii) Existing salinity levels may move landward due to rising sea levels. Since salinity has been shown to have a negative impact on fecal bacteria survival (Anderson et al., 1979), the size of condemned zones due to elevated fecal bacteria might be reduced if the current water quality standards are still used without regard to the influence of stormwater events.

iii) Increasing fecal bacteria loading from land due to increasing rainfall and runoff could be balanced by intensified UV radiation, changing salinity regimes, or other factors. Climate change might influence crop and livestock production, change species composition in forests, and contribute to the inundation and increased salinity of not only wildlife habitats, but also human dwellings. Therefore, it is hard to predict how fecal contamination levels would change spatially without carefully examination of the interaction among factors.

II) Temporal influence on fecal contamination from climate change:

i) Increased temperature with an unchanging rainfall pattern probably would prolong the period of time that a water body would exceed the water quality standards for safe swimming and shellfish harvesting, by simply affecting the activity of animals and the metabolism of bacteria on the land and water.

ii) If rainfall and runoff increase with a warmer climate, the fecal contamination levels may increase. But, if a hot summer with arid conditions occurs, fecal contamination might be reduced leading to improved water.

IV-5.7 Relationship between environmental variables and FC contamination

The complete tree from CART analysis explains a total of 42.7% of FC abundance variation. Given the high degree of variability of FC measurements and random events,

the ability to explain even half of this variability is remarkable (Kelsey et al., 2004). Although the unexplained variability may be too great to develop predictive equations, interpretation of the models reveals that specific land-use parameters can be identified as substantial contributors of fecal contamination and are important considerations for management of fecal pollution in the estuary (Kelsey et al., 2004).

Results from the CART analysis were generally consistent with expectation about primary variables affecting FC distribution in Virginia upstream coastal waters. It was expected that the variation in FC distribution would be related to the variables like land cover, residence time, and runoff potential. Highest FC concentrations occurred in watersheds with lower ratio (which means smaller watershed area compared to water area), longer residence time, higher runoff potential, and greater amounts of impervious surface and wetlands. The size of the watershed may indicate the distance fecal bacteria have to travel before entering the water. The longer the distance bacteria travel, the more opportunity for their levels to decay down to background levels. The positive relationship with water areas may reflect the probability of random dropping of feces from birds into the water. The direct release of feces into the water eliminates the transport loss of FC and correspondingly increases the possibility and degree of fecal pollution in the aquatic system. Longer residence times probably lead to FC bacteria accumulation since the existing waters take longer to be replaced. Higher runoff potential and greater impervious surface both provide a quick way to deliver FC bacteria into adjacent water bodies. When wetlands account for more than 5% of the whole watershed, wetlands could become a FC source, likely due to large amounts of wild animals living close to the waters. The second highest FC concentration interestingly occurred in about 12.5% watersheds with only one condition that the ratio value was greater than 76.35. This might be explained by the fact that large amounts of pollutants are being concentrated in small water bodies, which

results in higher FC concentrations. As expected, the lowest FC concentrations appeared in watersheds with low runoff potential, larger amounts of forest, as well as smaller ratio values.

Although cause and effect of fecal contamination has been demonstrated by many studies (Mallin et al., 2000; Van Dolah et al., 2000), growth and mortality kinetics of the FC bacteria, as well as how they relate to environmental variables are still under investigation. Management decisions must occur even without the luxury of complete knowledge of the system (NAS, 2000). Results from analogous situations, correlation models, and other empirical models may provide sufficient predictive abilities even though they do not incorporate a full understanding of the processes involved (NAS, 2000). In this study, results re-emphasize the importance of variables like land cover and residence time, and provide a reference for managers analyzing FC pollution from different watershed conditions.

It was unexpected that the CART analysis didn't show a strong relationship between FC concentration and cropland percentage, since agriculture has been associated with high levels of pollution, like fecal bacteria, nutrients, etc (Mehaffey, 2005). In many types of farming systems, poultry are raised confined in barns, and their manure is stored sometimes in extremely large holding tanks for several months prior to release on agricultural land or pasture land (Lu et al., 2005). In addition to the rich organic matter and minerals, studies have shown the presence and survival of pathogenic, or indicator bacteria in treated sludge (Paul et al. 1995a; Guardabassi et al. 1998; Iwane et al. 2001; Iversen et al. 2002; Vernozy-Rozand et al. 2002). Many of these organisms can survive for several months and multiply in sludge-amended soils (Straub et al. 1992, 1993; Tierney et al. 1997; Gibbs et al. 1997). There are growing concerns that such

land-applied manures or treated sewage sludge are making their way either through land runoff or airborne transmission into adjacent water systems and degrading the water quality (Carrington et al., 1998). Therefore the lack of agricultural influence on FC contamination levels is confusing.

There are several possible explanations for this unexpected result:

i) Land covers data accuracy:

Land cover used in the spatial analysis comes from the NLCD 1992 land cover dataset. NLCD 1992 was the first land-cover mapping project with a national (conterminous) scope. It is a set of consistent land cover maps at 30-m spatial resolution for the entire nation (Vogelmann et al., 2001). Stehman et al. (2003) conducted a study to assess the accuracy of the 1992 National Land-Cover Data (NLCD). Their results show that overall accuracies for Level I (7 major land cover types) and Level II (more detailed classification) are 70% and 43% for the Mid-Atlantic, including Virginia. Obviously, errors in NLCD 1992 can "average out" when using Levels 1, which is a broader land cover classification. The inaccuracies in land cover data may be transformed into a misleading representation of the real world when trying to relate the variables like land cover percentage to fecal contamination levels.

ii) Accuracy of other variables:

The accuracy of the research result is limited by the availability of existing data, incomplete understanding of influences on fecal pollution, data mis-representation of the real world, unintentional data processing errors, etc. The accuracy of other variables such as slope, all have the ability to contribute to the uncorrected result.

iii) No relationship between cropland and fecal contamination:

What makes cropland so different and why there is a great deal of attention on fecal contamination issues is the manure operations and application on this land surface.

Manure application doesn't occur continuously. Manure is spread on fields usually prior to crop-planting. Similarly, the timing of biosolid land applications must be scheduled around tillage, planting and harvesting operations and is influenced by crop, climate, and soil properties (Evanylo, 1999). A possible reason for the absence of a relationship between amount of cropland and FC levels is given by Hunter et al. (1992) in their effort to explain the negative relationship between FC concentration and water flow that occurred in 25% of their overland flow sites. They mentioned that when land surface water flow increased, an increased rate of bacterial removal from the local land store depleted this store sufficiently for a dilution in FC concentration to occur. Areas of land subject to continual water movement, and therefore bacterial removal at the surface, may be particularly prone to such depletion. Therefore, depletion of FC bacteria in the cropland soil, resulting from soil erodibility, growing season rainfall, and irrigation practices, might contribute to the absence of a relationship. This explanation could also be used to understand the results from the regional comparison which found the Eastern shore, which has large amounts of cropland, to have many low FC concentration values in its embayments compared to the other regions, while has also having slightly greater percentages of high FC concentration values than the Rappahannock and the Potomac Rivers. The depletion of FC bacteria in the land store during storm events may explain the high concentration values, and also account for the many low FC concentrations found which may represent conditions between rainfall events in areas having lots of cropland. Many studies on cropland make strong recommendations about manure storage and application to reduce fecal contamination from land. While these recommendations seem to offer effective management options for improving water quality, they also may convey a false impression that agriculture is the main source of fecal contamination in some waters (Boesch et al., 2001).

IV-6 Conclusions

The identification of watersheds characteristics influencing FC contamination patterns, as well as how contamination levels are expressed at different temporal and spatial scales can aid and guide successful management decisions.

One of the principal physical forcing mechanisms affecting the water quality in Virginia coastal waters is tidal variation. Since the analysis on tidal effects showed that there is clearly seasonal difference in FC levels between summer and winter and the difference due to seasonal change is much larger than the difference due to tidal effects, the results suggest that the proposed quantification process in next chapter may be better separated into two periods – the warm season and the cold season.

The increasing FC contamination levels along the tributaries from downstream to upstream do not conflict with previous studies. This consistent spatial pattern throughout Virginia coastal regions which have very varied patterns of land use implies that FC distribution differences between upstream, middle and downstream regions are mostly due to the gradient of salinity and tidal influence. It also suggests the importance of restoring water quality upstream in order to improve conditions downstream.

The comparison between different land-cover-dominated watersheds suggested that embayments in urban-dominated upstream watersheds were prone to higher fecal contamination than forest-dominated upstream watersheds. Embayments in forest-dominated watersheds have fecal contamination levels similar to those in cropland-pastureland-dominated watersheds. The result suggested that fecal contamination levels can be related to land cover. to the implication for the proposed

quantification approach in next chapter is that land cover could be used as a unit to quantify FC loadings from land.

Impervious surface areas reflect the gradients of human influence. Results from nonparametric changepoint analysis show there is significant change in fecal contamination levels when impervious cover percentage exceeds the values around 15%. This is similar to previous studies. Since few studies have revealed a threshold for development levels impacting safe shellfish harvesting, and none of the studies has identified a threshold based on analysis of such a large dataset, the result might offer a new basis for management of development practices in the future.

The broadest FC concentration range, as well as the highest incidence of elevated FC concentrations occurred in the James River. This may be attributable to the high percentage of developed land. The lowest FC concentration median values occurred along the Eastern Shore which was characterized by a large percentage of small FC concentration values, a small percentage of medium values, and a relatively larger percentage of high values compared to the Rappahannock and the Potomac Rivers. This pattern may be associated with the landscape characteristics of the Eastern Shore which include a flat land surface with small slope values and areas with quite intensive agricultural operations. The probability of exceeding a given FC concentration value is greater in the York than the Rappahannock Rivers. This may be explained by the differences in soil runoff potential. The Rappahannock River contains more soils with moderately low (B) runoff potential, while the York River contains more soils with moderate and high runoff potential.

The magnitude of FC levels may be determined by the intensity of rainfall, temperature, and water discharge. Rainfall, temperature and flow discharge together explained about 81% of data variation. These three natural forces create a challenge for pollutant reduction from land. Even though these natural forces cannot be controlled, there still is some ability to manage their influence, such as the installation of best management practices to reduce amounts of runoff from precipitation. Even though there is quite close relationship suggested by the visual comparison between temporal components of the dataset and these variables, it is also possible that other factors, such as storm frequency, play a significant role in determining the patterns observed.

Many studies try to reveal the relationship between FC concentration and different environmental variables. But few researchers have applied classification and regression tree analysis to predict or classify conditions affecting FC levels. Not all variables contribute equally to observed FC levels. In this study, environmental variables making significant contribution to the FC levels were determined to be impervious surface percentage, forest percentage, pasture percentage, wetland percentage, runoff potential, ratio of watershed area divided by water area, and residence time. The results for these variables show consistency with previous studies except for cropland. Explanations for this unexpected result are possibly due to inaccuracy of land cover data, but another explanation may lie in the patterns of FC bacteria export from cropland over time. The potential for short term and very high levels of FC discharge related to significant rainfall events may create a long term water quality record that with the statistical characteristics of the one used in this study.

This study provided a thorough examination of FC spatial and temporal distribution in Virginia coastal waters. It can offer some guidance for management goals within each of the river based regions that comprised the study area. For example, with limited resources,

management might be most efficiently targeted in upstream watersheds. Another example might be the seasonal pattern of sampling necessary to detect significant FC contamination problems.

V. QUANTIFICATION OF FC LOADING

V-1. Introduction

While waterways can be impaired in numerous ways, the protection from pathogenic microbe contamination is most important for waters used for human recreation, drinking water and aquaculture (Simpson et al., 2002). Most contamination in water is considered to originate from human and animal feces through direct or indirect dumping into water. To effectively manage fecal-contaminated water systems, pollutant sources must be identified and quantified prior to implementing remediation practices (USEPA, 2005). Generally accepted fecal pollution sources to coastal waters include point source discharges of treated and untreated sewage from shoreline outfalls and boats, and a variety of nonpoint sources, such as runoff from naturally vegetated areas (including wetlands), agricultural runoff, stormwater runoff from impervious surfaces associated with urban, commercial, or industrial land uses, malfunctioning or poorly-sited septic systems, and direct deposition of waterfowl feces (Weiskel et al., 1996). There is no single method that has emerged as a definitive answer to the source identification problem (Kelsey et al., 2008). Without accurate source identification, the study of quantification of FC loadings develops, as expected, slowly and less effectively. This problem affects the TMDL implementation in Chesapeake Bay, which as a national model, has to face the challenges of cleaning up bay water polluted partly by excess bacteria. It's absolutely necessary to accelerate the pace and come up with a way to quantify FC loadings.

Attempts to quantify the amount of indicator bacteria from pastures, grazing systems, cropland and feedlots have been tried in many studies (Miner et al., 1966; Kunkle, 1970; Doran and Linn, 1979; Young et al., 1980; Moore et al., 1988; Edward et al., 2000; Soupir et al., 2006; Mishra and Benham, 2008). For example, Reinelt and Horner (1995) estimated FC loadings were 4.2×10^{10} and 1.4×10^{9} organisms ha^{-1} $year^{-1}$ for urban and nonurban wetlands, respectively, in King County, Washington. Soupir et al. (2006) showed from their results that the flow-weighted *E. coli* bacteria concentrations were highest in runoff samples from the plots treated with cowpies (1.37×10^{5} cfu/100 ml), followed by liquid dairy manure (1.84×10^{4} cfu/100ml) and turkey litter (1.29×10^{4} cfu/100ml). However, most of the quantification efforts have been conducted on designed plots, not on real field observations. For example, an experiment by Soupir et al. (2006) was conducted with each transport plot 3 m wide by 18.3 m long on an approximate 5.5 percent slope. Although researchers try to deal with numerous challenges in designing fields hydrologically similar to the real situation, the development of quantification processes is still not mature since switching from local scales to large scales generally introduces greater variation due to increasing environmental impact and land use practices. The quantification of the amount of FC bacteria transported in runoff from different sources may also have been hindered by sampling protocols, parameter selection, cost concerns, and so on.

Currently, there are two approaches to quantify fecal bacteria pollutants from land that are used most often. The first approach uses watershed-scale models, as suggested by the EPA, such as HSPF, LSPC, or GWLF to generate loading information for reduction allocation. The watershed model simulates the daily FC loads from the watershed and discharges to the receiving water where a hydrodynamic model is used to simulate FC transport in the water column. Most watershed models are lumped-parameter models and

are driven mainly by precipitation. The accuracy of precipitation is quite important to determine the performance of watershed models. The estimation of fecal bacteria amount by these watershed models also highly depends on the data such as land use distribution, hydrologic data, livestock, wildlife, human population estimates, and FC production rates from human and/or animals. It is assumed that observed fecal data from water come from well-mixed estuary water, but this is not always true in real situations. In addition, population values and FC production rates are variable and poorly documented (Hyer and Moyer, 2004). Population values commonly are unknown for human, pet, and wildlife populations, and the proportion of the population that contributes to the instream FC load is also unknown (Hyer and Moyer, 2004). The variability of the data leads to large uncertainties in the estimation of FC loads from watersheds. The common way to "resolve" the problem of uncertainty is through model calibration. But the model calibration is subjective and often relies on visual comparison of model results against observations based on professional judgment (Shen et al., 2006). After careful calibration, it is still difficult to answer questions as to whether or not the derived solution is correct, how many other solutions are equally viable, and what degree of uncertainty is associated with loading estimation (Shen, et al., 2006). Even though some models, like HSPF, have been demonstrated to be an effective tool for simulating FC transport (Shen et al.,2005), the variation in data sources and uncertainty involved in model calibration limit the capability of models to successfully identify FC sources and quantify the loadings.

Another way to identify and quantify the sources of fecal bacteria is to use microbial source tracking (MST) technology. It has been used successfully to discriminate between ruminant and human fecal sources in fresh and marine waters (Boehm et al., 2003; Field et al., 2003; Gilpin et al., 2003). For example, sources of fecal pollution in Virginia's Blackwater River have been identified using antibiotic resistance analysis (ARA), a type

of MST, showing that livestock contributed the highest percentage of isolates (47.6%), followed by wildlife (29.1%), and human (24.9%) (Booth et al., 2003). The results from this research are being used to develop TMDL project allocations for FC in the Blackwater River. While results from MST studies could help significantly in the implementation of best management practices, there are a number of problems that need to be addressed, including the problems relating to detection limits, reproducibility of the assays, and temporal and spatial variability of markers (Simpson et al., 2002). The problem relating to temporal and spatial variability was more sophisticated in the estuary, which is influenced by tidal flushing. MST data alone from a sampling station can't provide sufficient information to separate upstream pollutants input from downstream pollutant sources, which could be possibly carried upstream by the rising tide. Beside these problems, it is still not clear how the MST technique could relate specific genes to measurement of fecal indicators in natural water (Shanks et al., 2006). There is no single method that has emerged as a definitive answer to the source identification problem (Kelsey et al., 2008). Without a definite answer to this problem, tone must be very careful when using the estimated quantification result from the MST method.

Because of large uncertainties involved in the determination of FC loads from watershed models and the problems of MST technology to identify FC sources, an alternative approach was proposed to use inverse modeling to derive the amount of FC loads from each land cover as a result of given FC concentrations in receiving waters, located in Virginia coastal watersheds with relatively small tidal embayments. Rather than a direct modeling approach, an inverse modeling approach can be interpreted as the meanings of the input and output functions are exchanged. The unknown variables of a direct model are treated as the known input functions of the inverse model, and the known variables of the direct model are treated as the unknown output functions of the inverse model (Bals

et al., 2003). Inverse modeling has been applied over a wide range of environmental problems including model parameter estimation (Yeh, 1986; Sun, 1994; Shen and Kuo, 1996; Shen et al., 2006; Yang and Hamrick, 2005), point source loading estimation (Piasecki and Katopodes, 1997), parameter estimation for virus transport (Barth and Hill, 2005), the determination of decay rates (Munavalli and Kumar, 2005), and estimation of nonpoint sources of FC (Shen et al., 2006).

The inverse modeling approach was applied twice in two closely connected steps. The result from one step was used as input for the next step. Firstly, the inverse modeling approach was used to backcalculate FC total loads for each watershed from observed FC concentrations in the receiving waters. Secondly, the derived FC total loads for each watershed were used as input to backcalculate FC loading rates for each individual land cover based on a linear model of FC deposition from these land covers. Here land cover was treated as a single fecal bacteria source and used as a management unit because of the large uncertainties in estimation of the amount of FC bacteria from each individual fecal source such as cattle, geese, and so on. The amount of fecal pollutants washed off by rainfall depends on the amount of feces that accumulated during the preceding dry period and the volume and velocity of runoff during a rain event (Simpson et al., 2002). Uncertainties in this proposed method include changing activities of humans and animals, unknown population sizes, varied and poorly documented FC production rates, durations of preceding dry period, FC decay rate, random events, and the variation in FC measurement, etc. All these factors complicate the issues regarding source quantification. Although using land cover as a management unit could not resolve all the problems, expanding the scale from each individual source up to a type of land cover could possibly aid the prediction of how external factors or processes will alter

some patterns (Urban et al., 1987). The variation of derived results may be reduced and the credibility of the results could be improved.

The derived FC loading rate for each land cover from the inverse modeling approach can be used to estimate the amount of FC bacteria coming from each individual watershed. A major improvement on the FC quantification process in this study was to inversely calculate FC loading rates, instead of estimating FC loading rates which later are adjusted by model calibration. As mentioned earlier, model calibration is quite tedious and subjective. It is hard to determine what degree of confidence one can have on the estimated FC loading rates after all these subjective adjustments. In this inverse modeling approach, FC loading rates from each land cover were treated as a set of unknown parameters instead of measured or estimated parameters that need adjustment by subjective model calibration. The advantage of the inverse modeling approach is to lower model complexity so the errors associated with the loading rates can be estimated (Shen et al., 2006). The model used to quantify loads is based on event mean concentration, land cover, rainfall, and hydrological properties of the watershed, such as runoff coefficients. FC event mean concentration (FCMC) was used to represent the FC loading rate with the unit of MPN/per unit area of land cover/per unit of rainfall. This means how much FC bacteria could be carried by one unit of rainfall from each type of land cover. The inverse modeling approach with derived FCMC could be used to quantify FC loadings from each land cover type instead of individual human or animal sources. The application of this approach may also aid and guide successful fecal bacteria source control and predict the impact on fecal contamination levels from land use change.

V-2. Materials and Methods

V-2.1 Study area

The research was conducted within Virginia coastal watersheds, located on southern Chesapeake Bay. The study sites were distributed in upstream regions. The climate of Virginia coastal regions can be characterized as humid with hot summers, mild winters, and a fairly uniform distribution of precipitation throughout the year. In January the average temperature along the Virginia coast is 4 degrees Celsius. In July the average temperature is about 26 degrees Celsius. Average annual precipitation is approximately 108 centimeters. Sem0i-diurnal tide is the major tidal pattern. Tide ranges from 0.6 meter to 1.0 meter. Forest (53%) and agricultural land (17%) comprise most of the land cover. In total 165 watersheds were delineated within the Virginia coastal region, occurring in the upstream areas of most rivers and their tributaries. These watersheds ranged in size from 369,388 to 173,718,943 m2, encompassing different land types.

V-2.2 Inverse approach

V-2.2.1 Pollutant loading estimation from land

The total fecal bacteria loading from a watershed can be derived from the linear combination of available FC amounts from each type of land cover. Here land cover was treated as the fecal bacteria source and used as a management unit. Total loading of FC from a watershed was given by

$$T = \Sigma \ (T_j) \qquad (1)$$

where T_j is total loading of bacteria in the surface runoff from land cover j on the watershed (MPN/unit time), and T is the sum of loading from a land cover.

It was assumed that there was a constant FC bacteria loading rate for each type of land cover, represented by FC event mean concentration (FCMC). Total loading of bacteria in the surface runoff from land cover j was derived from

$$T_j = FCMC_j \times Q_j \qquad (2)$$

where Q_j is the amount of surface runoff from land cover j (m^3/unit time), and $FCMC_j$ is FC event mean concentration for land cover j (MPN/unit of rainfall/per unit of area).

The total amount of annual runoff from a particular land cover area, Q_j is then derived as:

$$Q_j = R_j A_j \qquad (3)$$

where A_j is the area of each land cover (m^2), and R_j is total average annual surface runoff from land cover j (m). Therefore the total loading of bacteria from a watershed can be written as:

$$T = \Sigma \ (FCMC_j \times R_j \times A_j) \qquad (4)$$

The quantity of runoff is determined by one of the fundamental equations used in the Watershed Management Model (WMM):

$$R_j = [C_p + (C_i - C_p) IMP_j] I \qquad (5)$$

Where IMP_j is fractional imperviousness of land cover j, I is long-term average annual precipitation (m), C_p is the pervious area runoff coefficient, and C_i is the impervious area runoff coefficient. The WMM was developed specifically to estimate annual/seasonal non-point pollutant loads from direct runoff on watersheds and subbasins and was modified to address watershed management needs (WMM, 1998). It has been widely

applied for estimating different pollutant loads, such as nutrients and BOD (Shelley and Petrus, 2004; Sargaonkar, 2006; Gao, 2008). The assumption here is that the amount of storm water runoff from any given land cover is in direct proportion to annual rainfall, and the quantity of runoff is controlled by the fraction of the land cover category that is characterized as impervious (Sargaonkar, 2006).

V-2.2.2. Pollutant loads estimation from receiving water

Tidal Prism Water Quality Model (TPWQM) was developed in late 1970s at the Virginia Institute of Marine Science as a tool to assist water quality management of small coastal basins (Kuo and Neilson, 1988). The model simulates the physical transport and biochemical processes in a water body based on the concept of tidal flushing (Ketchum, 1951). That is, the water and material in the water exchange through the waterway due to the tidal flow and river flow. The kinetic portion of the TPWQM was later expanded by Kuo and Park (1994). The refined TPWQM has been successfully applied to the Lynnhaven River (Park et al., 1995), four other small coastal basins in Virginia (Kuo et al., 1998) and the Poquoson River in Virginia (Shen et al., 2002). The model was also adopted by the Virginia Department of Environmental Quality for their use in determining wastewater discharge permits in Virginia small coastal basins.

Since study areas are located in the headwaters of tidal rivers, characteristics of the transport processes for fecal bacteria depend primarily on water exchange with downstream regions and water discharge from the upland watershed. It was assumed that a single water segment represents a headwater water body, and the fecal bacteria are well mixed in the segment, as shown in Figure V-2.1. The mass balance of water can be written as follows (Guo and Lordi, 2000):

$$\frac{dV}{dT} = Q_{in} - Q_{out} + Q_f \qquad (6)$$

where Q_{in} is the quantity of water that enters the upstream water segment on the flood tide from downstream ($m^3 \bullet T^{-1}$); Q_{out} is the quantity of mixed water that leaves the upstream water segment on the ebb tide that did not enter the upstream on the previous flood tide ($m^3 \bullet T^{-1}$); Q_f is total freshwater input over the tidal cycle ($m^3 \bullet T^{-1}$); V is the volume of the upstream segment (m^3); and T is the dominant tidal period (hours).

When considering fecal bacteria transport processes, the mass balance of FC can be written as follows:

$$\frac{dVC}{dT} = Q_{in}C_{in} - Q_{out}C_{out} + L - kVC_{out} \qquad (7)$$

where L is the lateral pollutant loading from the upland watershed within the tidal cycle (MPN/tidal cycle), k is the fecal coliform decay rate (d^{-1}), C_{out} is FC concentration in the headwater segment (MPN/100ml), and C_{in} is the downstream FC concentration (MPN/100ml). In a steady-state condition, FC loads estimated from receiving waters can be back-calculated as follows:

$$L = Q_{out}C_{out} - Q_{in}C_{in} + kVC_{out} \qquad (8)$$

V-2.2.3. Inverse approach application

It is common practice to link watershed models with surface water models to estimate nonpoint source loads and simulate bacteria concentrations in estuaries and coastal embayments (Lahlou et al., 1998; Shen et al., 2005). Instead of estimating nonpoint source loads and then simulating bacteria concentrations, an inverse approach was applied to use measured bacteria concentrations to back-calculate bacteria loads from receiving waters and then allocate the value of bacteria loads into management units.

Again land cover was treated as a management unit. A combined equation from Equation 4 and Equation 8 was written as:

$$T = L \sum (FCMC_j \times R_j \times A_j) = Q_{out}C_{out} - Q_{in}C_{in} + kVC_{out} \quad (9)$$

A set of unknown FCMC for each type of land cover can be derived by solving multiple equations, each of which represent the number of FC delivered by unit rainwater in a watershed. After combining Equation 4 and Equation 8 into Equation 9, the problem associated with different time scales in one model has to be addressed. WMM was designed to estimate annual or seasonal long-term pollutant loads from land. TPWQM can only derive pollutant loads within a tidal cycle. Long-term average FC concentration in the water was used to represent the average fecal contamination level from tidal flushing, freshwater input, or sediment resuspension, etc. The pollutant loads estimated from WMM were then evenly distributed into a tidal cycle period since the goal of this study was to look at normal conditions instead of severe conditions such as storm events. The accuracy of derived FCMC greatly depends on the accuracy of the inverse estimation of FC loads from receiving waters. Because of the large uncertainties involved in the determination of FC loads from the land, the recent development of inverse modeling has provided an efficient approach for water quality modeling and loading estimation with the incorporation of observed data from the receiving water in the simulation (Piasecki and Katopodes, 1997; Zou et al., 2007; Shen et al., 2006; Wan and Vallino, 2005; Barth and Hill, 2005). The model experiment done by Shen et al. (2006) suggested that the error associated with the inverse load estimation with limited data is approximately 10% from the study conducted in the tidal Wye River on Maryland's Eastern Shore, USA. The advantage of this approach is that it provides a systematic way to quantify model errors and overcomes subjective model calibration, and the estuary dynamics and transport processes can be fully simulated (Shen et al., 2006).

V-2.2.4 Inverse approach applied on categorized watersheds

There were a total of 15 variables chosen to associate with FC contamination levels in 165 upstream watersheds. These variables were: impervious surface percentage, forest area, developed area, wetland area, crop area, pasture area, runoff potential, slope, drainage density, eccentricity, residence time, and ratio of watershed area to water area, watershed area, water area, and water volume. The GIS software ARCMAP 9.3 was used to extract the necessary data from GIS data layers. FC data used in this study were collected by the DSS monitoring survey. FC concentrations were extracted between 1994 and 1998, and their geometric means were calculated during this five-year period. These five-year averages of FC concentrations were used to better represent seasonal average conditions in each watershed to correspond with land cover data. NOAA Coastal Change Analysis Program (C-CAP) 1996 land cover data was used in this study to estimate land and water area and percentage of each land cover. Mid-Atlantic Regional Earth Science Center (RESAC) impervious surface maps are available for 1990 and 2000, so RESAC 2000 impervious data were used for the calculation. It was assumed that there were not significant changes for the impervious cover during the 4 years from 1996 and 2000. The STATSGO database was used to determine the hydrologic soil runoff potential. The primary soil attribute used in STATSGO is the hydrologic soil group (A, B, C, D). Group A and Group B were grouped together to represent low runoff potential soils, while Group C and D were grouped as high runoff potential soils. Soil drainage condition in a watershed was determined by total area of low runoff potential soils divided by total area of high runoff potential soils. The slope estimates for each watershed were the averaged value from all the individual slope of grid cells inside the watershed using the USGS DEM dataset. Drainage density was calculated by dividing the total length of the stream within a watershed by its watershed area based on the National Hydrography Dataset (NHD) dataset. Another hydrograph parameter considered was watershed eccentricity

(Black, 1972) which takes into consideration the unique shape of watersheds. The eccentricity equation is shown here:

$$\tau = (|L_c^2 - W_L^2|)^{0.5} / W_L$$

where τ = watershed eccentricity, a dimensionless parameter, L_C = length from the outlet to the center of mass of the watershed, and W_L = width of the watershed perpendicular to L_C and at the basin's center of mass, both in the same units (m). Low values of τ are found to be associated with high flood peak potential and high values of τ with low flood peaks (Black, 1996). The residence time, *RT*, is an estimate of time required to replace the existing pollutant concentration (or water) in a system; it can be calculated as follows: $RT = V_b / Q_b$, where V_b is mean volume of the embayment, and Q_b is the quantity of mixed water that leaves the bay on the ebb tide that did not enter the bay on the previous flood tides (m^3 per tidal cycle). In a steady-state condition, the mass balance equations for the water can be written as follows: $Q_b = Q_o + Q_f$, where Q_f is total freshwater input over the tidal cycle (m^3), and Q_o is the volume of new ocean water entering the embayment on the flood tide, which can be determined by the use of the ocean tidal exchange ratio β as: $Q_o = \beta * Q_T$, where Q_T is the total ocean water entering the bay on the flood tide (equal to water surface area multiplied by tidal range). β is defined as the ratio of new ocean water to total volume of water that enters the estuary during a flood tide (Fisher et al., 1979). Usually, the return ratio was set as 0.7, as previous studies suggested for a Virginia coastal embayment (Kuo et al., 1998).

The CART method was applied to account for FC concentration variability as a function of the variables mentioned above. Cluster analysis was then applied to the variables derived from the CART analysis. In each cluster of watersheds, the total FC loading in each watershed derived from the WMM equaled the hydrological model calculation result of the total FC loading from the TPWQM, as shown in Equation 9 (where

$R_j = C_p + (C_i - C_p)IMP_j]I$). In any given system, values of the runoff coefficient vary from 0.05 to 0.95 (ASCE, 1992). Runoff coefficients applied in this study use the average value of the range and the values were slightly adjusted for seasonal differences as shown in Table V-2.1. Seasonal impacts on FC abundance were considered based on the results of PC1 in Figure IV-4.6.5. FC abundance is obviously higher in the months from April to October, but lower in the months from November to March. Here the period from April to October is considered the warm season, and the cold season is from November to March. Annual and monthly precipitation was derived by averaging monthly precipitation data in three Virginia cities (Norfolk, Richmond, and Williamsburg) extracted from the National Climatic Data Center with the aid of the Climatology Office at the University of Virginia. Available precipitation data in Norfolk is from 1/1/1946 to 12/31/2008, from 8/1/1948 to 12/31/2008 in Williamsburg, and from 8/1/1948 to 12/31/2008 in Richmond. Monthly water discharge data for the western side of Chesapeake Bay was averaged from daily stream flow data during the period between 1/1/1984 and 12/31/1996 from USGS gaging station 01661800 located in the headwaters of Great Wicomico River, VA. Water discharge data from USGS gaging station 01844800 located in the headwaters of Nassawadox Creek, VA was used for the Eastern Shore. Values of the FC decay rate range from 0.5 to 3.0 per day in salt water (Thomann and Mueller, 1987; Mancini, 1978). A constant bacteria decay rate of 1.0 d^{-1} was used for the warm season, and 0.3 d^{-1} for the cold season, which is a common practice in water quality modeling (Shen and Zhao, 2009). There were five unknown variables: FCMC of forest, urban, cropland, pastureland, and wetland. This means the values of each FCMC could be derived only if there were at least five equations. The FCMCs for each group were obtained by a least squares method that used the minimal sum of the deviations from the given set of data. Watersheds in each group are supposed to have similar FC

mean concentrations (FCMCs), which were derived for each land cover and had the unit of MPN per square meter per inch of rainfall.

V-2.2.5 Alternate Approach: Inverse calculation on land-cover-dominated watersheds

An alternate approach was used as well, in order to help explain unexpected results due to large uncertainties, as well as variations in FC measurements. For example, negative FCMC values could possibly result from the inverse calculation method. In the alternate approach, an ideal situation was assumed where a watershed was only occupied by one land cover type. This ideal situation would simplify all the inverse calculation processes and avoid unexpected results such as negative FCMC values. Although this ideal situation didn't exist at the scales of studied watersheds, this exercise still provides useful information. An approximate situation is a watershed dominated by a single land cover, the percentage of which exceeds 70 -80 % of the whole watershed area. Cropland and pastureland were combined together because each occupies less than 60% of the total watershed and neither could be regarded as the dominant land cover with a criterion set as 70%. The standard for a watershed to be called a single land-cover-dominated watershed is designated as follows: A "forest-dominated" watershed is one with forestland occupying more than 80% of the entire watershed area. A "crop-pastureland-dominated" watershed is one for which the cropland and pastureland together occupy about 70% of the entire watershed. An "urban-dominated" watershed is one with more than 70% land as developed area. It was assumed that total FC loads from a watershed all come from this dominant land cover. Based on this assumption, $FCMC_{dominant}$ can be derived from the following equation, for both warm and cold seasons, based on Equation (9):

$$FCMC_{dominant} R_{dominant} A_{dominant} = Q_{out} C_{out} - Q_{in} C_{in} + kVC_{out} \qquad (10)$$

V-3 Results

V-3.1 Inverse calculation on categorized watersheds

The variables output from the CART analysis were supposed to contribute significantly to the FC levels. These variables were impervious surface percentage, forest percentage, pasture percentage, wetland percentage, ratio of watershed area divided by water area, and residence time as shown in Figure IV-4.7.2. Cluster analysis was applied to these variables derived from the CART analysis. Paul et al. (2006) mentioned that, in the current study, there was no clear guidance from any of the criteria for the number of clusters. After an initial analysis based on criteria described in the statistic software Minitab 15 where the abrupt change in the similarity levels determines the number of clusters, the result was 5 clusters (i.e. 5 groups) of watersheds (Figure V-3.1) utilizing the Manhattan Distance and Complete Linkage method. The clusters have 78, 56, 20, 7, and 4 watersheds as shown in Figure V-3.2. There are problems with the results. Table V-3.1 shows the results of Group 2, which has 56 watersheds, as an example. In Table V-3.1, the value of the coefficient for each variable is the value of FCMC for each type of land cover. Pasture has a negative value, which is incorrect. After trying to force the constant to equal a minimum of zero, several negative values still exist.

V-3.2 Alternate approach: Inverse calculation on land-cover-dominated watersheds

Since there were some negative values in the derived FCMC values using the inverse approach, the alternate approach was applied for further analysis. Selected upstream watersheds were shown in Table IV-4.3.1. Each watershed is dominated by one type of land cover. Derived FCMCs for three types of land cover (forest, urban, and

crop-pastureland) and their standard deviations are given in Table V-3.2 for both warm and cold seasons. The data show that FCMCs are similar to each other in the warm season with forest having the smallest values. FCMCs in urban areas during the cold season are less than FCMCs in urban areas during the warm season. During the cold season, FCMCs in urban areas are about one order of magnitude higher than FCMCs in forest and crop-pastureland.

V-4. Model Verification

It is often said that all models are wrong but some are useful. Uncertainty exists in any model because of imperfect representations of the real world. Thus it is necessary to verify the model performance and check carefully to ensure the model reflects a reasonable reality. Model verification in this study was performed by using literature data, analytical data, and available observed data.

V-4.1 Model verification from literature data

From the literature data, FC loadings estimated by Reinelt and Horner (1995) were 4.2×10^{10} and 1.4×10^{9} organisms ha^{-1} $year^{-1}$ for the urban and non-urban wetlands, respectively, in King County, Washington. According to the records at the University of Washington station in Seattle, mean annual precipitation is about 34.78 inches in King County, Washington. Total FC loading can then be converted to the unit defined as FC generated per m^2 of surface per inch of rainfall. Weiskel et al. (1996) related total FC loads, defined as the FC generated per m^2 of surface per centimeter of rainfall, to the surrounding land use. Since the author provided the area for associated land use, total FC loading can also be converted to the unit defined as FC generated per m^2 of surface per inch of rainfall. Table V-3.3 shows the comparison between the estimated FC mean concentration in this study and the mean concentrations from previous studies, mentioned

above, but converted to the same units as this study. Previous studies did not separate FC loading into seasons, which makes the verification more difficult. Overall, the magnitudes of estimated FC mean concentrations are close to each other among similar land conditions, even though the research sites are located in different areas: one is in King County, Washington (Reinelt and Horner, 1995), one is in Buttermilk Bay, Massachusetts (Weiskel et al. 1996), and this study is in Chesapeake Bay, Virginia. The previous studies suggest that the estimated FCMCs were reasonable.

V-4.2 Model verification from analytic data

The accuracy of the results was also evaluated through the comparison between the estimated total FC loading using FCMCs and the calculated total FC loading using TPWQM in all 165 upstream watersheds. The estimated total FC loadings were obtained by summing the FC loadings from each individual land cover. FC loadings from each individual land cover were calculated by applying FCMC in the equation: FCMC * Runoff * Land cover area. This calculation is based on land processes. The calculated total FC load using TPWQM is based on processes occurring in the water. Since FC concentration in the water depends on hydrodynamic processes (such as flushing) and biological process (such as FC decay), total FC loading from the land is back-calculated after considering these processes in the water. TPWQM simulates net water flow over a tidal cycle and can be coupled with observed FC concentrations and FC decay rate to produce total FC loadings from land at steady state. Figure V-3.4 shows the log-transformed comparison both in warm and cold seasons between the estimated and the calculated total FC loadings over a wide range of FC total loadings. In general, estimated loadings agree well with FCMC derived FC total loading, with R square equaling 0.54. Figure V-3.6 shows the same comparison but with actual values (not log-transformed). Like the log-transformed comparison, they match well with each other

except for a watershed in the warm season and several in the cold season. No specific reasons have been found to explain their differences. The comparison suggests that FCMCs offer a simple, but effective way to quantify the fecal contamination sources based on land cover.

V-4.3 Model verification from observed data

In order to better verify the accuracy of the FCMCs, four watersheds with the greatest land cover change from 1984 to 2005 (using C-CAP 1984 and C-CAP 2005 land cover datasets) were selected to test the FCMCs reliability. Selected watersheds and their major land cover change are shown in Table V-3.4. Watershed 52_M1_UP, 58_M1_UP, 58_M2_UP, AND 63_M3_UP show the urban areas increasing by 35%, 40%, 25% and 27%, respectively. Without changing any parameter values used in the equations, such as runoff coefficients, between 1984 and 2005. Figure V-3.8 shows the comparison between observed FC concentration percentage changes and estimated total FC loading percentage changes. The assumption for this comparison was that nothing changed in the hydrodynamic processes (such as streamflow or return ratio) and biological processes (FC decay rate) in these watersheds' receiving waters. From the graph, all the observed FC concentrations show an increasing trend during this 21-year period indicating percentage increases. One can also notice the same trend from the estimated FC total loading with all the percentage increases. This similar trend suggests that FCMC can capture the increasing phase of observed FC concentration variability during these years.

The magnitude of the percentage change, however, is different; most of the estimated FC total loading percentage changes are smaller than the observed FC concentration percentage changes, especially in the warm season. There are a few reasons to explain this discrepancy. One of the possibilities is due to the inaccuracy of the impervious data.

The impervious data used in this study was from 1990 and 2000, but the time period for land cover change is from 1984 to 2005. The accuracy of the result is largely limited by the difference in the data collection and availability. The second reason is likely due to the assumption that there was no change in streamflow discharge from 1984 to 2005. Jennings and Jarnagin (2002) observed that historical changes in streamflow in the upper Accotink Creek subwatershed (close to Annandale, Virginia) appear to be related to increases in anthropogenic impervious surface cover. The third reason is that the same set of runoff coefficients was used in both 1984 and 2005. In the cold or warm season for each individual year, runoff coefficients only varied for different land covers but didn't vary between watersheds. Even though the same kind of land cover existed in the two watersheds, physical characteristics of the two land areas would differentiate them from each other, such as slope, percentage of vegetation cover, and so on. Strictly speaking, runoff coefficients should be given different values to reflect the discrepancies among watersheds. But in the classical "rational formula" (Dooge, 1957) the runoff coefficient is considered to be a constant, differing in value between different types of surface cover of a watershed. Whether the runoff coefficient can be considered a constant has been a controversial question in hydrology (Gottschalk and Weingartner, 1998). Lütschg-Loetscher (1945) sums up the problem as follows: "In spite of the fact that Karl Fischer (1934) and Walter Wundt (1937) have expressed their opinion repeatedly and in depth, the erroneous opinion is at hand still here and there that the value of this relation (the runoff coefficient) for a certain drainage basin is a hydrographic constant, so that by changing precipitation runoff can be determined in advance or, vice versa, the precipitation can be determined from the runoff." Unit hydrographs, including rainfall volumes and runoff coefficients, have been extensively studied by Weingartner (1989) for 17 well-equipped Swiss drainage basins with an area ranging between 5 and 200 km^2. From his work, runoff coefficients could at least be influenced by altitude, slope, river

network density, and soil permeability, etc. Therefore, using the same set of runoff coefficients for both 1984 and 2005 introduces errors in the estimation of percentage changes in terms of FC total loading.

V-5 Discussion

V-5.1 Inverse calculation on categorized watersheds

Even though the inverse calculation on categorized watersheds didn't result in expected results, it still appears to be a theoretically correct approach to obtain FCMCs. The purpose of using cluster analysis was to group watersheds that have similar watershed characteristics and, hence, have similar fecal contamination levels. Such a grouping scheme would be helpful in reducing the cost of restoration of water quality by restricting the development of the TMDL to one or two representative water bodies under a single group and applying the knowledge to other water bodies in the same group (Paul et al., 2006). There were some negative values in the results, which are incorrect. But it is possible to get these negative values since the derived values (FCMCs) vary in a large range due to individual watershed differences, amount of data collection, natural variability, random events, and the variation in FC measurements, etc. The estimation of total FC loadings was based on an additive model and assumes linear processes, which was probably an incomplete representation compared to the reality. The loadings can potentially overestimate or underestimate the impacts of land cover on fecal contamination.

V-5.2 Alternate approach: Inverse calculation on land-cover-dominated watersheds

The alternate approach tried to avoid the production of negative FCMC values and switched the target from watersheds with mixed types of land cover to watersheds with

one dominant land cover. This approach produced two sets of FCMCs, one for the warm season, and one for the cold season. The similarity of FCMCs for different land covers in the warm season can be explained by the increased outdoor activities of domestic animals, increasing movement and behavior of wildlife, and manure spreading on fields during the growing season. The forest FCMCs having the lowest values could be probably attributed to the vegetation and its special soil infiltration capability. In a typical forested ecosystem, approximately 40% of the precipitation is returned to the atmosphere by evapotranspiration, and approximately 50% infiltrates into the soil, with the remaining 10% returned to receiving waters via surface runoff (e.g., Dunne and Leopold, 1978; Harbor, 1994; Arnold and Gibbons, 1996). FCMCs in urban areas during the cold season were less than FCMCs in urban areas during the warm season. The major reason for this is probably due to decreased precipitation in the cold season compared to warm season. During the cold season, FCMCs in urban areas are about one order of magnitude higher than FCMCs in forest and crop-pastureland. Major FC sources from urban areas are through on-site septic tanks or combined sewer overflow, while FC sources from non-urban areas are mostly carried by runoff and/or through direct feces deposition into water. The time domestic and wild animals spend on the fields and accessing the water possibly determines the amount of potential FC loadings. Human activities were not affected by season as much as domestic animals and wildlife, and it is reasonable to obtain larger FCMCs in urban than in non-urban areas. In many cases, the hydrology in urban areas has been severely altered to allow for urban development, which has resulted in an increase in the amount of impervious surfaces, and subsequently, a drastic rise in the volume of runoff that ultimately may cause combined sewer overflow in some areas (McLellan et al., 2007). This is probably one of the reasons why urban areas are the focal point of the fecal contamination issues. The issues about how to deal with human wastes remain one of the most difficult environmental and fiscal challenges in the United States

(Heaney et al. 1999). Much of the population increase is occurring in rural areas that are typically not served by municipal wastewater facilities, resulting in the expanded use of on-site wastewater disposal systems. Although removal efficiencies in properly functioning drain fields are high (Hagedorn et al., 1981; Reneau et al., 1989), there is only limited FC purification of wastewater within a septic tank (Reay, 2004). Recent studies suggested that failing septic tanks might pose a serious risk for human source fecal contamination (Scheuler, 1999). In many municipal areas, urban stormwater is discharged directly into waterways with no treatment. Urban stormwater and sewage overflow are still considered major sources of water-body impairment in the U.S. (USEPA, 2004).

One of the advantages of using FCMCs is that they can fit easily into a spreadsheet to estimate fecal bacteria loadings and can be coupled with any hydrologic simulation to produce bacteria loads. Their uncertainty was represented as FC mean concentration plus a standard deviation in warm and cold seasons, respectively. However, the FCMCs will have little value unless they are used with site-specific information, such as the spatial and temporal information from land and water.

V-5.3 Model sensitivity test

Assembling the types of data necessary for running and calibrating a model is typically expensive and time consuming (NRC, 2000). Therefore, a sensitivity test run before using the model can provide two benefits. One is that the sensitivity test often indicates the relative importance of model input parameters and indicates which parameters should receive the most management attention (NRC, 2000). Another is that the potential effect of errors inherent to the model must be considered before evaluating the effect of errors

in field measurements, in orderto prepare model input data (Swain et al., 2008). So the purpose of the sensitivity test is to become familiar with the model before any effort is made collecting and processing the data.

A model sensitivity test was performed by adjusting four parameters (pervious area runoff coefficient, impervious area runoff coefficient, return ratio in one tidal cycle, and fecal bacteria decay rate in the water) with $\pm 20\%$ variation to see how much change the output values (FCMC values) would undergo. Since the limitations associated with FC measurements are one possible source of errors in the estimation of FCMC values, the sensitivity was also tested on the FC concentrations inside and outside of the water segment with a $\pm 20\%$ variation in order to look at responses of the values of FCMCs.

Among the four parameters (pervious area runoff coefficient, impervious area runoff coefficient, return ratio in one tidal cycle, and fecal bacteria decay rate in the water), FC decay rate and pervious runoff coefficient are the two most sensitive parameters to the value of FCMCs as shown in Table V-4.1. Changing the return ratio by 20% only induced about 5% absolute difference in the value of the output variable FCMCs. Changing the FC decay rate by 20% induced an absolute difference of approximately 14% in the value of FCMCs, which is similar to the standard deviation of FCMCs. If the fraction of impervious land is small, like forest-dominated watersheds, FCMC is more sensitive to the pervious runoff coefficient. In land with a small percentage of impervious surfaces, the percentage of precipitation that appears as runoff from these pervious land surfaces receives the most management attention on fecal contamination issues. If the fraction of impervious land is large, for example in urban-dominated watersheds, output variables (FCMCs) have similar sensitivity to the other three input variables -- FC decay rate, pervious runoff potential, and impervious runoff potential. This means that

management of fecal contamination has broader considerations in land with high percentages of impervious surface.

The limitations associated with FC measurements are also one possible source of error in the estimation of FCMCs. The Most Probable Number (MPN) method is applied by DSS for the enumeration of FC. Gronewold and Wolpert (2008) mentioned that estimating procedures for MPN have intrinsic variability and are subject to additional uncertainty arising from minor variations in experimental protocol. The MPN estimates are highly variable because this function has a very broad peak and so are close to its maximum value over a wide range of possible concentrations. The sensitivity was tested on the FC concentrations inside and outside of the water segment. Changing the FC concentration inside of the water segment (C_{out}) by 20% induced about 25% absolute difference in the value of the output variable FCMCs. Changing the FC concentration outside of water segment (C_{in}) by 20% only induces about 7% of a difference. Thus the FC error characteristics are different for inside and outside water segment measurements.

V-5.4 How to improve the model?

There are several things that could be done to improve the analytical strength of the data as well as the reliability of the results.

1. Check the values of runoff coefficients to ensure that runoff coefficients for each land cover in each watershed reflect reasonable physical reality, since these coefficients often hide a degree of uncertainty.
2. Consider the grouping of land cover categories to be used in the analysis. In this study, grassland was put into the land cover as pastureland, and scrub/shrub was put into the land cover as forest. Since the categorization was supposed to group land

with similar characteristics, the groupings would partially determine the accuracy of the results. For example, should open space in urban areas or bare land be put into the urban category or another land cover category?

3. Have data collected from the outlets draining a single land cover in individual watershed. These data would be helpful in the quantification processes. However, there are few coordinated efforts to maintain a database of samples collected from outlets downstream of a single land cover region. Such a database would be valuable for developing loading estimates of receiving waters, for model calibration, and for the purposes of developing simplified relationships between concentration, loads, and causative factors.

V-6 Conclusions

Protection from fecal microbial contamination is one of the challenges to safeguard water quality. Environmental management of fecal contamination has forced many states and federal agencies to allocate pollution reduction responsibility using management units to reduce fecal pollutants released from land and transported in runoff to water. For an effective management of fecal pollution processes, it is important to quantify fecal bacteria sources in relation to commonly used management units. In this study, fecal bacteria sources are quantified as a function of land cover (land cover area, land cover runoff coefficients, impervious condition). Here each kind of land cover is a management unit. The derived FCMCs for land covers provide an easy way to estimate the amount of fecal bacteria coming from any individual land cover and offer a reference, which could assist the allocation of pollution reduction responsibility.

The model developed in this study avoids the problems associated with using highly varied and poorly documented FC production rates and population numbers. Although

the model is simple, the magnitude of FCMC values based on land covers effectively distinguished the seasonal FC loadings and captures the difference between land covers. The quantification of FC bacteria sources based on land cover could make it easier for managers to assign land cover based accountability to restore fecal contaminated environment. In general, FCMCs provide suggestions for the effective management of fecal contamination in water systems. The derived FCMCs can also be powerful parameters for predicting effects of land cover change on fecal contamination issues. The accuracy and reliability of the suggestions and predictions is dependent on how FCMCs are used. Incorporation of site-specific information is necessary to understand how different sources contribute to the pollution in any single watershed.

VI. SUMMARY

This study provided the first comprehensive examination of FC spatial and temporal distribution in the Virginia portion of Chesapeake Bay. Based on the information from FC spatial and temporal distributions, fecal bacteria loadings from land were quantified as a function of land cover from this research. FC quantification processes were a relatively easy but efficient way to estimate the amount of fecal bacteria coming from different land sources.

By describing how fecal contamination levels are distributed at different spatial and temporal scales and the resulting patterns, this research demonstrated several interesting findings. 1) The analysis on tidal effects showed that there was clearly seasonal differences in FC levels between summer and winter, and the differences due to seasonal change were much larger than the differences due to tidal effects. FC quantification must account for seasonal variation rather than tidal variation. 2) The consistent spatial pattern throughout Virginia coastal regions inferred that FC distribution differences among upstream, middle and downstream regions were mostly due to the gradient of salinity and tidal influence. Restoring water quality upstream may help improve water quality downstream. 3) The results from the comparison between different land-cover-dominated watersheds suggested that fecal contamination levels respond differently between urban-dominated, forest-dominated and crop-pastureland-dominated watersheds, reflecting the different characteristics among these contrasting land covers. The effect of land cover on the quantification approach supports the use of land cover as a unit to quantify FC loadings from land. 4) Investigation of impervious surface areas using

Nonparametric Changepoint Analysis demonstrated that the threshold value for impervious surfaces expanding due to development was 15%. In a watershed whose impervious surface percentage exceeds this threshold, water quality has a high possibility of being seriously impaired from fecal contamination. Even though threshold values have been mentioned in previous research, none of the studies identified threshold values using such large amount of data, especially in Virginia coastal regions. 5) The probability to exceed a given FC concentration value is greatest in the James River, followed by the York and the Rappahannock Rivers, with the lowest occurring on Eastern Shore. This pattern could probably be associated with the landscape characteristics of the different river systems, resulting in different management decisions. 6) Previous studies described physical factors as having important effects on fecal pollution. This study demonstrated that the magnitude of FC levels may be determined by the intensity of rainfall, temperature, and water discharge. Rainfall, temperature and flow discharge together explained about 81% of data variation. 7) Environmental variables making significant contributions to FC levels were determined to be impervious surface percentage, forest percentage, pasture percentage, wetland percentage, runoff potential, ratio of watershed area divided by water area, and residence time based on classification and regression tree analysis. Quantifying the magnitude of the contribution of environmental variables to fecal contamination levels has not been studied in previous research. This study also raises some interesting points for future research, such as the large contributions from wetlands compared to forest and pastureland, and no significant contribution of fecal contamination from cropland. Even though there are some limitations in the dataset, the author believes that the results offer valid insights and ideas for additional research.

In addition to the investigation of FC spatial and temporal distribution patterns, another core contribution from this study is that FC loadings are quantified as a function of land

cover based on real data, not estimates of the number of wild and domestic animals living in the study sites. The model developed in this study avoids the problems associated with using highly variable and poorly documented population numbers and FC production rates. Although the model is simple, the magnitude of Fecal Coliform Event Mean Concentration (FCMC) values based on land covers effectively distinguished the seasonal FC loadings and captured the difference between land covers. The derived FCMC is a very useful variable which can be used to calculate FC loading from each land cover. Actually, it provides a very practical suggestion for effective management of fecal contamination, for example, in the development of TMDLs to deal with excess bacteria in coastal waters. It also is easier for managers to assign land-cover-based accountability to help restore fecally contaminated environments.

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TABLES

Table IV-3.6.1: Monthly means of precipitation, temperature, and flow discharge in Virginia coastal regions. Monthly means of precipitation and temperature were calculated as average of data from 1946 to 2008 in three cities (Norfolk, Richmond, and Williamsburg). Monthly water flow discharges were calculated based on daily stream flow data during the period between 1984 and 1996 from USGS gaging station in the headwaters of Great Wicomico River, VA.

Month	Precipitation (inches/month)	Temperature (F)	Flow Discharge (cubic feet/second)
1	3.56	39.57	1.75
2	3.30	42.54	1.95
3	3.88	49.09	2.55
4	2.92	57.73	1.87
5	3.90	66.50	0.96
6	3.75	74.47	0.37
7	5.17	79.05	0.52
8	5.01	76.93	0.91
9	4.10	71.48	0.40
10	3.57	61.14	0.64
11	3.13	52.26	1.02
12	3.33	43.66	1.18

Note: Monthly precipitation and temperature were from the National Climatic Data Center www.ncdc.noaa.gov/oa/climate/climatedata.html), with the aid of the Climatology Office at University of Virginia (http://climate.virginia.edu). Monthly water discharges were averaged from USGS data (http://va.water.usgs.gov).

Table IV- 3.7.1: Fifteen predictor variables used in Classification And Regression Tree statistical analysis to associate environmental condition with fecal contamination levels in 165 upstream watersheds

Watershed	FC GEOMEAN	Imperviousl 990 (%)	Slope	Drainage Density	Eccentri-ci ty	Urban	Forest	Pasture	Cropland	Wetland	Water Area	Ratio	Residence Time	Water Volume	Watershed area	Runoff Potential
1_M1_UP	34.09	0.40	20.63	0.0006	2.25	0.04	0.76	0.03	0.12	0.04	512736	76.35	1.77	249840	39147175	1.64
10_B1_UP	18.65	0.13	10.38	0.0011	0.71	0.01	0.60	0.20	0.18	0.01	131097	27.02	3.17	68040	3542208	2.08
10_M1_UP	20.90	0.30	9.58	0.001	0.51	0.04	0.63	0.21	0.10	0.01	367526	25.95	3.61	216450	9538112	4.30
11_M1_UP	21.06	1.29	7.14	0.0039	0.92	0.53	0.28	0.16	0.03	0.01	48037	3.48	3.33	30150	167102	2.56
12_M1_UP	21.76	1.98	6.96	0.0038	0.16	0.25	0.49	0.12	0.12	0.02	2653993	3.22	9.60	4796370	8554795	1.52
13_B1_UP1	29.58	0.06	28.05	0.0009	0.80	0.04	0.75	0.10	0.09	0.03	136180	82.15	1.26	43560	11187120	8.73
13_B1_UP2	15.55	0.08	27.12	0.0015	0.70	0.01	0.83	0.08	0.06	0.02	174455	39.26	3.15	119970	6848703	21.89
13_B1_UP3	18.23	0.30	18.47	0.0018	0.79	0.00	0.55	0.29	0.15	0.01	99238	45.39	3.42	75870	4504387	7.00
13_M1_UP	38.26	0.10	21.99	0.0012	0.84	0.04	0.71	0.11	0.11	0.03	753582	104.35	1.60	328680	78634091	6.70
14_M1_UP	21.76	0.09	19.52	0.0011	0.53	0.05	0.65	0.18	0.10	0.02	570742	46.29	3.30	505620	26418149	8.69
15_B1_UP1	17.11	0.00	9.37	0.0013	1.77	0.01	0.55	0.28	0.17	0.00	23001	72.18	0.77	4500	1660199	1.62
15_B1_UP2	18.48	0.06	13.95	0.0021	0.67	0.00	0.57	0.28	0.13	0.01	53486	64.79	1.53	20340	3465279	2.42
15_B1_UP3	14.48	0.07	8.01	0.0005	0.81	0.02	0.83	0.08	0.05	0.02	111584	27.01	2.62	63360	3013510	0.30
15_B1_UP4	10.20	0.00	4.93	0.001	0.94	0.00	0.68	0.06	0.23	0.03	14960	24.69	1.18	3780	369388	0.26
15_B1_UP5	10.45	0.04	3.74	0.0005	0.96	0.00	0.82	0.05	0.10	0.03	27638	33.56	1.45	8910	927491	0.24
15_M1_UP	18.22	0.07	5.41	0.0006	0.70	0.08	0.54	0.21	0.05	0.11	199037	26.60	2.74	117900	5294761	0.44
16_B1_UP1	29.80	3.62	11.72	0.002	1.01	0.17	0.51	0.11	0.20	0.02	149451	18.27	5.14	154170	2730409	1.65
16_B1_UP2	20.01	1.53	9.39	0.002	1.62	0.08	0.60	0.07	0.25	0.01	85170	10.83	3.91	64800	922812	1.28
16_B1_UP3	18.11	0.27	9.28	0.0018	0.68	0.06	0.37	0.06	0.51	0.01	76505	21.83	3.22	50130	1669826	1.43
16_M1_UP	20.56	0.24	6.19	0.0017	0.94	0.02	0.60	0.07	0.24	0.07	353537	18.16	3.50	248490	6420187	0.21
16_M2_UP	23.54	0.72	13.78	0.0014	0.72	0.04	0.64	0.18	0.12	0.02	263487	49.42	3.61	215640	13021494	3.05
16_M3_UP	21.12	0.23	6.09	0.001	0.66	0.01	0.66	0.10	0.16	0.06	186037	15.51	3.45	127260	2885181	0.42
2_M1_UP	32.50	2.04	4.50	0.001	0.76	0.11	0.67	0.07	0.08	0.07	1671519	12.40	2.18	1053090	20722216	0.13
2_M2_UP	29.26	0.51	14.41	0.0012	0.71	0.04	0.67	0.09	0.17	0.04	1309784	51.14	2.16	906120	66985842	0.72
20_M1_UP	18.94	0.66	16.72	0.0012	0.57	0.10	0.60	0.19	0.10	0.01	540516	10.79	4.78	562230	5831052	2.80
20_M2_UP	20.19	1.56	12.57	0.0011	0.90	0.10	0.60	0.14	0.15	0.02	151054	42.03	2.46	90450	6348527	3.47

20_M3_UP	9.17	0.56	7.72	0.0017	0.87	0.04	0.33	0.37	0.26	0.01	101542	11.00	4.02	88920	1116871	0.89
21_B1_UP1	20.09	0.00	19.18	0.0008	0.74	0.02	0.75	0.12	0.10	0.01	53409	46.23	1.33	18360	2469114	14.05
21_B2_UP	13.97	0.18	23.29	0.0013	0.99	0.00	0.76	0.11	0.12	0.01	46138	62.70	1.50	18900	2892660	11.05
21_M1_UP	24.43	0.13	19.74	0.0011	0.70	0.03	0.73	0.10	0.12	0.03	1401375	66.76	2.78	1075770	93553787	8.02
21_M2_UP	39.63	0.67	19.72	0.0012	0.96	0.07	0.67	0.11	0.13	0.02	823881	66.35	2.37	537570	54663019	8.56
22_M1_UP	21.39	0.21	11.19	0.0009	0.71	0.18	0.52	0.18	0.12	0.01	134782	29.14	0.83	29250	3927692	1.88
23_M1_UP	17.47	0.06	20.23	0.001	0.64	0.06	0.71	0.10	0.10	0.04	895288	68.84	1.42	396810	61635890	4.05
23_M2_UP	10.51	0.07	4.93	0.001	0.33	0.05	0.68	0.06	0.18	0.03	153537	28.49	1.37	58590	4374072	0.48
23_M3_UP	15.10	0.08	16.50	0.001	0.50	0.02	0.75	0.06	0.16	0.01	108622	39.88	0.85	26640	4332106	1.92
24_M1_UP	14.46	0.09	22.62	0.001	0.43	0.08	0.67	0.09	0.10	0.05	899714	48.68	0.85	227430	43796778	1.62
25_M1_UP	16.98	0.21	23.50	0.001	0.77	0.03	0.60	0.17	0.15	0.05	2338752	74.28	1.10	844740	173718943	3.49
25_M2_UP	28.58	0.12	17.38	0.001	0.56	0.01	0.63	0.15	0.16	0.05	327781	68.40	0.96	102150	22419998	1.28
25A_M1_UP	19.03	0.34	7.84	0.0017	0.67	0.01	0.36	0.19	0.25	0.19	353415	55.49	1.45	159840	19609673	0.42
26_M1_UP	14.26	1.03	29.29	0.0011	0.27	0.01	0.68	0.12	0.14	0.05	5572	424.23	0.21	720	2363592	1.25
27_M1_UP	22.84	0.05	24.83	0.0011	0.42	0.03	0.79	0.08	0.06	0.05	404335	50.95	0.97	111960	20601684	0.65
28_M1_UP	19.42	0.13	20.87	0.0011	0.81	0.03	0.57	0.20	0.16	0.04	1086449	33.97	0.82	231840	36907110	0.93
29_M1_UP	12.76	0.69	27.51	0.001	0.87	0.04	0.75	0.08	0.12	0.02	1119714	19.98	1.56	460800	22367700	0.49
30_M1_UP	16.80	0.31	21.79	0.0014	0.65	0.01	0.61	0.19	0.16	0.03	501237	15.07	1.34	156960	7553290	1.72
31_M1_UP	19.90	0.19	11.79	0.0008	0.16	0.00	0.58	0.21	0.19	0.01	163001	29.66	1.97	81900	4835021	2.38
31_M2_UP	24.54	0.33	14.92	0.0009	0.91	0.00	0.55	0.23	0.19	0.02	286004	36.86	1.95	145260	10542308	1.14
32_M1_UP	19.11	0.63	16.23	0.001	0.73	0.09	0.37	0.34	0.18	0.02	258012	18.31	1.00	54990	4724458	8.15
32_M2_UP	26.19	1.19	10.22	0.0019	0.47	0.15	0.16	0.35	0.32	0.01	118964	17.28	3.39	85230	2055773	1.93
33_M1_UP	13.78	6.48	6.60	0.0046	0.61	0.53	0.29	0.06	0.11	0.01	177762	4.03	3.39	129870	715900	0.06
33_M2_UP	23.75	10.22	8.50	0.0029	0.87	0.69	0.20	0.04	0.05	0.02	18777	10.18	2.48	10260	191205	0.19
33_M3_UP	15.95	3.88	10.12	0.0037	0.61	0.37	0.23	0.15	0.25	0.01	207759	5.33	5.36	241200	1108327	0.66
33_M4_UP	19.36	2.53	5.89	0.0032	0.68	0.13	0.41	0.14	0.29	0.03	71979	9.17	1.87	29520	659844	0.13
34_M1_UP	28.92	1.25	12.43	0.0012	0.88	0.05	0.44	0.33	0.18	0.01	99988	39.66	2.06	54180	3965672	7.28
34_M2_UP	26.96	0.22	15.81	0.0012	0.21	0.02	0.64	0.16	0.17	0.02	162251	73.02	2.14	101070	11847128	1.28
34_M3_UP	12.88	0.70	7.32	0.0005	0.72	0.05	0.62	0.09	0.23	0.01	115579	37.91	2.18	65880	4382020	0.75
35_B1_UP	26.16	0.07	18.79	0.0008	0.51	0.00	0.82	0.04	0.10	0.05	108528	234.01	0.62	32220	25396997	0.85
35_B2_UP	15.15	0.15	19.42	0.0009	0.45	0.00	0.83	0.01	0.09	0.07	192337	85.31	1.36	92520	16407615	0.74
35_M1_UP	21.70	0.35	15.57	0.0011	0.84	0.01	0.69	0.09	0.13	0.08	3481855	27.60	2.31	2457990	96110254	0.46
37_B1_UP1	14.42	0.54	4.78	0.0004	0.47	0.02	0.62	0.03	0.17	0.16	54719	52.01	1.78	21150	2846142	0.10
37_B1_UP2	14.35	0.03	4.79	0.0008	0.85	0.00	0.47	0.05	0.07	0.40	207851	17.28	2.99	116910	3590657	0.15
37_M1_UP	16.26	0.40	3.57	0.0011	0.73	0.01	0.34	0.05	0.10	0.49	60392	73.80	1.25	17820	4456904	0.03
39_M1_UP	39.61	0.52	2.79	0.0011	0.74	0.00	0.33	0.13	0.37	0.17	4497	84.49	0.12	180	379917	0.00

4_B1_UP	18.81	0.80	35.42	0.0014	0.87	0.02	0.64	0.14	0.16	0.05	147476	120.92	1.00	53910	17832559	6.37
4_B2_UP	13.42	0.10	2.30	0.0012	0.81	0.00	0.27	0.06	0.52	0.14	48900	26.90	1.27	17910	1315241	0.08
4_M1_UP	17.51	0.22	21.98	0.0009	0.75	0.01	0.49	0.27	0.19	0.04	1366090	71.63	2.70	1198980	97856136	7.43
4_M2_UP	27.57	0.31	3.31	0.0007	0.91	0.03	0.38	0.14	0.26	0.19	229177	25.12	1.56	102240	5757540	0.30
41_B1_UP	36.47	1.64	3.63	0.0012	0.90	0.06	0.55	0.05	0.10	0.24	152320	43.07	0.70	49140	6559710	0.05
41_M1_UP	21.78	0.11	3.15	0.001	0.93	0.04	0.57	0.03	0.05	0.31	358982	47.19	0.48	79110	16941908	0.12
42_B1_UP	17.09	0.11	4.16	0.0006	0.72	0.09	0.58	0.19	0.11	0.03	184069	18.99	0.89	63360	3494730	0.19
43_B1_UP1	16.21	0.87	10.10	0.0007	0.45	0.01	0.71	0.08	0.08	0.13	196353	64.81	0.46	38160	12725366	0.18
43_B1_UP2	26.51	0.03	6.00	0.0003	0.59	0.13	0.42	0.11	0.13	0.21	68826	45.86	0.44	12420	3156114	0.07
43_M1_UP	46.88	0.53	13.10	0.0009	0.83	0.02	0.72	0.07	0.09	0.10	1156318	104.60	0.81	430830	120950165	0.57
44_B1_UP2	30.00	1.29	5.15	0.0028	0.74	0.03	0.65	0.03	0.07	0.22	147415	47.82	1.01	28260	7049012	0.09
44_B1_UP3	51.54	0.64	3.97	0.0007	0.84	0.09	0.55	0.04	0.27	0.05	95937	18.72	1.01	16020	1795515	0.09
44_M1_UP	19.84	0.56	5.90	0.0007	0.85	0.06	0.54	0.06	0.10	0.24	135139	91.89	0.71	21780	12417783	0.09
46_B1_UP	29.57	5.25	6.94	0.0011	0.58	0.18	0.42	0.07	0.27	0.06	442863	14.94	1.45	269820	6618157	0.98
46_M1_UP	21.74	1.79	4.56	0.0014	0.64	0.26	0.45	0.13	0.10	0.07	238666	15.07	1.14	114390	3597682	0.34
46_M2_UP	22.82	0.60	4.12	0.0018	0.87	0.05	0.49	0.12	0.23	0.12	196638	14.01	0.85	69930	2755631	0.15
47_M1_UP	37.73	1.19	9.18	0.001	0.81	0.05	0.42	0.15	0.22	0.16	545211	18.71	0.65	172620	10198527	0.92
47_M2_UP	23.08	0.19	9.98	0.0011	0.48	0.00	0.54	0.07	0.18	0.21	188055	29.47	0.37	34200	5541816	0.52
47A_M2_UP	33.14	0.18	12.55	0.0014	0.67	0.00	0.54	0.16	0.22	0.07	205223	39.28	0.33	34380	8062035	0.63
47A_M3_UP	48.48	0.13	14.29	0.001	0.69	0.00	0.60	0.13	0.18	0.08	136351	77.55	0.29	21060	10573533	1.79
47A_M4_UP	26.00	0.24	14.40	0.0016	0.73	0.00	0.64	0.10	0.19	0.07	56933	129.62	0.22	7200	7379936	1.45
48_M1_UP	18.87	0.14	8.15	0.0009	0.76	0.00	0.54	0.09	0.08	0.28	337204	23.90	0.39	48780	8059699	0.45
48_M2_UP	20.88	0.16	21.20	0.001	0.58	0.01	0.75	0.07	0.10	0.08	1532761	60.37	1.35	820980	92535416	0.57
49_M1_UP	29.74	0.25	12.60	0.001	0.69	0.00	0.69	0.15	0.11	0.05	91981	206.81	0.18	11880	19022622	0.23
5_B1_UP	26.66	0.22	1.87	0.0005	0.86	0.00	0.82	0.01	0.06	0.11	14012	86.80	0.53	2520	1216189	0.19
5_M1_UP	34.88	0.23	7.85	0.0011	0.97	0.02	0.43	0.17	0.25	0.13	679201	35.47	2.23	445320	24093301	0.60
50_M1_UP	33.19	0.57	31.12	0.0013	0.86	0.02	0.69	0.10	0.13	0.07	262019	219.55	0.31	38340	57526426	0.38
50_M2_UP	52.28	0.18	39.76	0.0011	0.84	0.00	0.74	0.08	0.10	0.08	54901	182.72	0.24	5760	10031647	0.23
50_M3_UP	38.26	1.85	30.19	0.0011	0.68	0.03	0.71	0.08	0.10	0.07	181465	176.28	0.30	23580	31989441	0.27
50_M4_UP	20.03	0.48	27.98	0.0008	0.58	0.02	0.79	0.06	0.05	0.08	78276	208.41	0.25	9000	16313670	0.05
51_M1_UP	26.66	4.28	25.51	0.001	0.83	0.14	0.71	0.02	0.04	0.09	676633	56.29	1.38	439470	38087279	0.06
51_M2_UP	24.64	3.27	26.21	0.0012	0.81	0.09	0.76	0.03	0.05	0.06	544403	35.69	0.40	98100	19430800	0.04
52_B1_UP	13.77	2.18	17.79	0.001	0.83	0.12	0.71	0.09	0.06	0.01	263806	24.30	1.04	112320	6411531	0.07
52_M1_UP	20.12	2.62	12.95	0.0011	0.31	0.13	0.68	0.10	0.07	0.02	359915	11.43	0.77	109890	4115113	0.23
53_B1_UP1	4.68	1.07	5.53	0.0013	0.86	0.02	0.73	0.10	0.12	0.03	183137	12.05	0.52	41310	2206408	0.00
53_B1_UP3	4.13	3.99	4.69	0.0008	0.80	0.11	0.66	0.04	0.18	0.01	363238	13.17	0.66	104940	4782164	0.00

53_B1_UP4	4.42	9.08	7.52	0.0021	0.61	0.52	0.33	0.05	0.07	0.04	274974	6.17	0.90	106650	1696711	0.07
53_B1_UP5	5.90	4.85	7.56	0.0017	0.75	0.19	0.65	0.05	0.08	0.03	729519	18.58	1.29	414900	13555323	0.03
53_B1_UP6	4.71	3.42	4.66	0.0047	0.90	0.39	0.49	0.05	0.06	0.02	258735	5.78	0.91	101250	1495378	0.00
53_M1_UP	5.74	4.24	7.09	0.0013	0.70	0.18	0.61	0.09	0.06	0.06	856879	47.42	0.66	264150	40630367	0.03
53_M2_UP	5.59	11.85	5.18	0.0006	0.73	0.24	0.61	0.10	0.02	0.02	213245	17.31	0.63	58860	3692281	0.03
54_B1_UP2	20.65	23.06	4.84	0.0011	0.31	0.60	0.17	0.08	0.08	0.07	376882	11.85	0.65	102420	4466261	0.00
54_B2_UP1	20.51	10.88	6.49	0.0013	0.26	0.34	0.47	0.03	0.06	0.10	737854	53.53	0.44	144900	39498671	0.06
54_B2_UP2	13.76	5.66	4.64	0.0017	0.23	0.15	0.59	0.04	0.12	0.11	139492	37.80	0.36	21780	5272976	0.01
54_B2_UP3	15.87	13.78	4.14	0.0007	0.56	0.30	0.23	0.26	0.12	0.09	169637	47.62	0.37	27810	8078816	0.00
54_M1_UP	22.74	32.54	5.80	0.001	0.24	0.71	0.13	0.11	0.02	0.04	3056378	16.99	0.89	1149480	51940022	0.03
58_M1_UP	28.62	16.54	12.37	0.0009	0.68	0.43	0.40	0.08	0.05	0.04	412932	38.49	0.69	139050	15893659	0.00
58_M2_UP	29.03	15.28	9.85	0.0012	0.89	0.43	0.36	0.07	0.05	0.08	3085773	16.78	1.35	1974780	51782306	0.00
6_M1_UP	22.66	0.17	12.27	0.0012	0.47	0.01	0.49	0.24	0.18	0.08	302012	39.14	1.33	110610	11820308	2.39
6_M2_UP	18.59	0.17	8.02	0.0009	1.40	0.00	0.32	0.24	0.24	0.20	258957	30.11	1.23	85500	7796484	0.88
6_M3_UP	23.74	0.24	4.10	0.001	0.94	0.01	0.47	0.12	0.15	0.26	154384	24.18	0.86	34920	3732977	0.20
60_M1_UP	29.73	0.45	9.55	0.0007	0.59	0.02	0.59	0.09	0.19	0.10	551182	77.74	2.44	587160	42850723	0.06
61_B1_UP	46.25	2.93	8.75	0.0016	0.73	0.08	0.46	0.11	0.21	0.14	901021	27.70	1.45	676350	24960096	0.08
61_M1_UP	55.73	2.16	14.97	0.001	0.82	0.05	0.44	0.15	0.26	0.09	4540183	21.14	1.47	3414960	95994228	0.13
62_M1_UP	37.87	1.09	10.07	0.0012	0.64	0.05	0.42	0.15	0.26	0.12	3300572	20.48	0.79	1335240	67590762	0.21
63_M1_UP	15.74	3.14	7.68	0.001	0.63	0.06	0.15	0.13	0.36	0.29	747836	38.46	0.43	186840	28762280	0.09
63_M2_UP	28.46	6.38	10.72	0.0013	0.75	0.40	0.23	0.06	0.14	0.17	350670	24.51	0.30	59220	8595436	0.20
63_M3_UP	17.52	2.56	10.13	0.0018	0.81	0.24	0.28	0.21	0.16	0.11	32344	43.93	0.20	3780	1420920	0.51
7_B1_UP	23.56	0.32	23.01	0.0011	0.41	0.03	0.46	0.24	0.23	0.04	236783	43.15	3.36	208350	10217520	22.28
7_B3_UP	22.43	0.56	21.61	0.0012	0.50	0.03	0.47	0.29	0.19	0.02	238067	67.15	2.43	162990	15987013	5.12
7_M1_UP	17.32	0.22	24.23	0.0009	0.76	0.01	0.51	0.26	0.18	0.04	512185	71.58	2.66	389160	36661856	10.34
7_M2_UP	16.06	0.14	7.47	0.0008	0.48	0.02	0.50	0.19	0.20	0.09	96385	59.38	1.99	52830	5722890	2.77
7_M3_UP	27.85	0.85	21.00	0.001	0.33	0.03	0.52	0.25	0.18	0.01	604912	38.84	3.52	549810	23494720	4.89
70_M1_UP	35.57	29.50	8.37	0.0015	0.53	0.68	0.21	0.09	0.00	0.02	3544376	10.73	1.29	1577520	38040024	0.63
70_M2_UP	50.50	26.63	7.32	0.0014	0.56	0.58	0.15	0.15	0.04	0.07	3556074	16.25	1.20	1488330	57770263	0.18
76_M1_UP	14.83	0.41	1.88	0.002	1.20	0.05	0.55	0.10	0.17	0.14	419732	99.60	0.43	83070	41806285	0.23
76_M2_UP	12.91	0.36	3.36	0.001	0.94	0.02	0.42	0.23	0.25	0.09	289287	65.14	0.66	83160	18845162	1.04
76_M3_UP	11.68	0.07	2.58	0.0011	1.68	0.00	0.56	0.11	0.14	0.19	178141	50.86	0.52	39420	9059636	0.25
77_M1_UP	28.92	0.53	4.08	0.001	0.47	0.03	0.41	0.24	0.30	0.02	470880	55.20	0.81	159570	25991332	1.20
77_M2_UP	34.94	1.32	3.82	0.0013	1.35	0.04	0.43	0.28	0.15	0.10	282430	51.76	0.56	65250	14619440	0.89
77_M3_UP	33.20	0.89	2.86	0.0009	0.69	0.08	0.43	0.22	0.24	0.03	440039	69.23	0.64	119970	30466080	0.71
79_M1_UP	40.50	0.31	2.12	0.001	0.54	0.00	0.59	0.21	0.19	0.02	210677	25.64	0.67	52920	5401940	0.40

8_B1_UP1	28.70	0.32	23.52	0.0012	0.79	0.01	0.56	0.28	0.14	0.02	268924	49.16	2.52	171630	13221032	12.92
8_B1_UP2	24.28	0.01	22.64	0.0011	1.20	0.00	0.61	0.18	0.18	0.03	57145	34.13	2.12	29160	1950450	23.13
8_B1_UP3	18.34	0.11	8.94	0.0012	0.47	0.01	0.23	0.44	0.31	0.00	31274	23.63	2.76	19980	738930	1.36
8_M1_UP	29.68	0.19	24.43	0.001	0.24	0.03	0.61	0.23	0.10	0.03	696278	44.43	3.39	588060	30938803	9.32
8_M2_UP	18.81	0.41	10.54	0.0013	0.82	0.03	0.36	0.39	0.19	0.03	163875	22.99	2.45	92700	3767187	1.59
8_M3_UP	14.56	1.75	7.95	0.0034	0.61	0.00	0.22	0.37	0.41	0.00	80405	4.59	5.02	87210	369071	1.21
80_M1_UP	21.26	2.57	4.02	0.001	0.83	0.12	0.41	0.25	0.21	0.02	991604	23.55	2.98	996210	23356163	1.27
80_M2_UP	28.56	0.18	2.24	0.0012	0.24	0.00	0.58	0.10	0.29	0.03	138678	15.97	0.87	40050	2215179	0.57
80_M3_UP	23.50	0.10	1.81	0.0008	0.42	0.00	0.66	0.13	0.19	0.02	115439	31.09	0.65	25920	3589320	0.09
81_M1_UP	31.58	0.55	4.62	0.001	0.70	0.03	0.50	0.17	0.29	0.02	996256	31.56	1.41	457830	31437333	1.31
81_M2_UP	32.68	0.12	3.43	0.001	0.67	0.00	0.50	0.25	0.23	0.01	422056	44.45	0.91	129870	18761131	1.35
82_B1_UP1	31.02	0.09	3.44	0.001	2.26	0.01	0.37	0.19	0.41	0.01	58911	53.78	0.56	10710	3168268	3.99
82_M1_UP	37.50	0.16	2.82	0.001	0.93	0.01	0.49	0.31	0.17	0.02	393265	21.30	1.54	179010	8376786	0.89
84_M1_UP	29.39	0.71	4.08	0.0009	0.76	0.02	0.42	0.29	0.26	0.02	698556	44.28	1.43	336420	30930690	2.95
85_B1_UP1	18.36	0.71	3.67	0.0005	0.41	0.02	0.43	0.26	0.28	0.01	205708	51.48	0.95	70200	10590359	1.61
85_B1_UP2	17.93	2.07	3.92	0.0005	0.69	0.06	0.31	0.27	0.33	0.02	485993	24.09	1.02	168390	11709053	5.50
85_B1_UP3	17.57	0.80	3.26	0.0008	0.60	0.02	0.33	0.32	0.31	0.02	210293	55.82	1.11	85320	11738755	1.99
85_M1_UP	28.32	2.07	3.70	0.0007	1.03	0.03	0.43	0.19	0.33	0.02	389390	42.14	1.08	144540	16408089	1.58
86_B1_UP1	16.36	0.61	3.52	0.0008	0.45	0.03	0.44	0.31	0.18	0.03	217118	31.26	0.96	40140	6786145	2.77
86_B1_UP2	18.43	0.78	4.39	0.0007	0.56	0.01	0.44	0.25	0.27	0.03	198634	31.59	0.97	37260	6274175	3.82
86_M1_UP	12.89	0.38	3.06	0.0008	0.44	0.01	0.39	0.28	0.27	0.05	398263	22.40	0.99	73620	8921051	3.34
86_M2_UP	17.63	0.34	5.18	0.001	0.89	0.01	0.30	0.36	0.30	0.04	431821	23.83	1.52	123480	10288497	13.22
87_M1_UP	19.56	1.07	3.36	0.0006	0.60	0.03	0.36	0.45	0.14	0.03	259259	30.57	0.54	46620	7924894	6.36
88_B1_UP	31.87	2.72	5.01	0.0004	1.06	0.01	0.16	0.44	0.36	0.02	38564	44.31	0.44	6390	1708960	15.02
88_M1_UP	34.20	3.48	4.83	0.0008	0.29	0.05	0.24	0.35	0.33	0.03	109215	33.46	0.54	21510	3654194	7.56
9_M1_UP	24.23	0.01	7.41	0.0012	0.39	0.00	0.62	0.20	0.17	0.01	112701	23.77	2.20	56160	2678986	1.22
9_M2_UP	23.98	0.11	6.91	0.0009	1.24	0.00	0.75	0.14	0.09	0.01	97205	31.25	1.60	36000	3038100	1.45
9_M3_UP	30.21	0.05	21.96	0.0011	0.81	0.00	0.70	0.14	0.14	0.02	517650	36.49	3.58	433890	18888456	13.79
9_M4_UP	22.01	0.09	7.81	0.0009	0.42	0.00	0.80	0.09	0.08	0.03	526855	13.45	0.81	94140	7088724	2.43
90_M1_UP	17.96	1.52	4.11	0.0008	0.79	0.02	0.26	0.39	0.30	0.03	119124	47.34	0.25	13230	5638788	16.19
94_M1_UP	26.72	1.87	5.27	0.0013	0.64	0.01	0.52	0.16	0.28	0.03	119042	44.30	1.33	20700	5273737	6.70

Table IV-4.2.1: Areas of upstream watersheds. Delineation was based on the EOF results and the number of DSS water quality monitoring stations in their receiving waters.

Sub-watershed	Area (m2)	Number of Stations	Sub-watershed	Area (m2)	Number of Stations	Sub-watershed	Area (m2)	Number of Stations
1_M1_UP	39147175	3	34_M3_UP	4382020	1	21_B1_UP1	2469114	1
10_B1_UP	3542208	1	35_B1_UP	25396997	1	21_B1_UP2	3325128	1
10_M1_UP	9538112	3	35_B2_UP	16407615	1	21_B1_UP3	610259	1
100_M1_UP	35553748	2	35_M1_UP	96110254	3	21_B1_UP4	881349	1
11_M1_UP	167102	1	37_B1_UP1	2846142	1	21_B2_UP	2892660	1
12_M1_UP	8554795	3	37_B1_UP2	3590657	3	21_M1_UP	93553787	5
13_B1_UP1	11187120	1	37_M1_UP	4456904	2	21_M2_UP	54663019	7
13_B1_UP2	6848703	1	37_M2_UP	13035259	5	22_M1_UP	3927692	2
13_B1_UP3	4504387	1	39_M1_UP	379917	1	23_M1_UP	61635890	3
13_B1_UP4	3800558	2	4_B1_UP	17832559	1	23_M2_UP	4374072	1
13_M1_UP	78634091	1	4_B2_UP	1315241	1	23_M3_UP	4332106	1
14_M1_UP	26418149	2	4_M1_UP	97856136	3	24_M1_UP	43796778	5
15_B1_UP1	1660199	1	4_M2_UP	5757540	2	25_M1_UP	173718943	4
15_B1_UP2	3465279	1	41_B1_UP	6559710	2	25_M2_UP	22419998	2
15_B1_UP3	3013510	3	41_M1_UP	16941908	1	25A_M1_UP	19609673	1
15_B1_UP4	369388	1	42_B1_UP	3494730	4	26_M1_UP	2363592	1
15_B1_UP5	927491	1	43_B1_UP1	12725366	2	26A_M1_UP	20822804	1
15_M1_UP	5294761	3	43_B1_UP2	3156114	1	26A_M2_UP	73687291	2
16_B1_UP1	2730409	5	43_M1_UP	120950165	8	27_M1_UP	20601684	3
16_B1_UP2	922812	2	44_B1_UP1	7579563	1	28_M1_UP	36907110	5
16_B1_UP3	1669826	1	44_B1_UP2	7049012	2	29_M1_UP	22367700	2
16_B2_UP	239005	1	44_B1_UP3	1795515	3	30_M1_UP	7553290	3
16_M1_UP	6420187	3	44_M1_UP	12417783	1	31_M1_UP	4835021	1
16_M2_UP	13021494	3	46_B1_UP	6618157	6	31_M2_UP	10542308	2
16_M3_UP	2885181	2	46_M1_UP	3597682	2	32_M1_UP	4724458	3
1A_B1_UP	11851128	3	46_M2_UP	2755631	3	32_M2_UP	2055773	2
1A_M1_UP	94505000	2	47_M1_UP	10198527	9	33_M1_UP	715900	3
2_M1_UP	20722216	4	47_M2_UP	5541816	2	33_M2_UP	191205	1
2_M2_UP	66985842	4	47A_M1_UP	20900563	4	33_M3_UP	1108327	3
20_M1_UP	5831052	11	47A_M2_UP	8062035	2	33_M4_UP	659844	1
20_M2_UP	6348527	1	47A_M3_UP	10573533	4	34_M1_UP	3965672	2
20_M3_UP	1116871	2	47A_M4_UP	7379936	1	34_M2_UP	11847128	1

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Sub-watershed	Area (m2)	Number of Stations	Sub-watershed	Area (m2)	Number of Stations	Sub-watershed	Area (m2)	Number of Stations
48_M1_UP	8059699	3	60_M1_UP	42850723	1	80_M3_UP	3589320	1
48_M2_UP	92535416	3	60_M2_UP	1690344	1	81_M1_UP	31437333	5
49_M1_UP	19022622	2	61_B1_UP	24960096	10	81_M2_UP	18761131	2
5_B1_UP	1216189	1	61_M1_UP	95994228	10	82_B1_UP1	3168268	1
5_M1_UP	24093301	4	62_M1_UP	67590762	12	82_B1_UP2	2663258	1
50_M1_UP	57526426	3	63_M1_UP	28762280	1	82_M1_UP	8376786	4
50_M2_UP	10031647	3	63_M2_UP	8595436	4	84_M1_UP	30930690	2
50_M3_UP	31989441	2	63_M3_UP	1420920	1	85_B1_UP1	10590359	1
50_M4_UP	16313670	1	7_B1_UP	10217520	2	85_B1_UP2	11709053	3
51_M1_UP	38087279	3	7_B3_UP	15987013	1	85_B1_UP3	11738755	1
51_M2_UP	19430800	3	7_M1_UP	36661856	5	85_M1_UP	16408089	2
52_B1_UP	6411531	1	7_M2_UP	5722890	1	86_B1_UP1	6786145	1
52_M1_UP	4115113	3	7_M3_UP	23494720	5	86_B1_UP2	6274175	1
53_B1_UP1	2206408	3	70_M1_UP	38040024	6	86_M1_UP	8921051	2
53_B1_UP2	450736	1	70_M2_UP	57770263	3	86_M2_UP	10288497	3
53_B1_UP3	4782164	3	73_M1_UP	5444992	1	87_M1_UP	7924894	2
53_B1_UP4	1696711	3	76_M1_UP	41806285	3	88_B1_UP	1708960	1
53_B1_UP5	13555323	6	76_M2_UP	18845162	1	88_M1_UP	3654194	3
53_B1_UP6	1495378	1	76_M3_UP	9059636	1	9_M1_UP	2678986	1
53_M1_UP	40630367	4	77_M1_UP	25991332	3	9_M2_UP	3038100	1
53_M2_UP	3692281	3	77_M2_UP	14619440	3	9_M3_UP	18888456	4
54_B1_UP1	928519	2	77_M3_UP	30466080	2	9_M4_UP	7088724	5
54_B1_UP2	4466261	2	79_M1_UP	5401940	3	90_M1_UP	5638788	1
54_B2_UP1	39498671	3	8_B1_UP1	13221032	2	94_M1_UP	5273737	2
54_B2_UP2	5272976	1	8_B1_UP2	1950450	1	95_M1_UP	9929727	1
54_B2_UP3	8078816	3	8_B1_UP3	738930	1	97_M1_UP	15387866	3
54_M1_UP	51940022	2	8_M1_UP	30938803	5	98_M1_UP	22647950	3
58_M1_UP	15893659	3	8_M2_UP	3767187	1	99_M1_UP	28800993	5
58_M2_UP	51782306	6	8_M3_UP	369071	1			
6_M1_UP	11820308	2	80_M1_UP	23356163	4			
6_M2_UP	7796484	2	80_M2_UP	2215179	1			
6_M3_UP	3732977	1						

Table IV-4.3.1: Selected upstream watersheds that are dominated by one type of land cover (using criteria described in the text), for the analysis of land cover effect on fecal contamination levels.

Land cover	Subwatershds	Dominated Land Cover Percentage	GA station	Number of FC Observations
Crop-Pasture	8_B1_UP3	0.7506	8-34	53
	8_M3_UP	0.7949	8-27	54
	82_B1_UP2	0.7546	82-6B	46
	88_B1_UP	0.8054	88-21	54
	94_M1_UP	0.7046	94-3W	59
	94_M1_UP		94-3X	58
Forest	13_B1_UP1	O.8237	13-21	51
	13_B1_UP2	0.8488	13-16	53
	21_B1_UP1	0.8171	21-43	53
	27_M1_UP	0.853	27-6	52
	27_M1_UP		27-7	52
	27_M1_UP		27-8	50
Urban	53_B1_UP4	0.7153	53-44.1	58
	53_B1_UP4		53-44.2Z	57
	53_B1_UP4		53-44.5	58
	54_B1_UP2	0.7207	54-30	57
	54_B1_UP2		54-31	55
	54_M1_UP	0.8495	54-23	57
	54_M1_UP		54-24	57
	70_M1_UP	0.8004	70-10	60
	70_M1_UP		70-11	60
	70_M1_UP		70-12	60
	70_M1_UP		70-7	60
	70_M1_UP		70-8	60
	70_M1_UP		70-9	60
	70_M2_UP	0.7559	70-17	60
	70_M2_UP		70-24	60
	70_M2_UP		70-25	60

Table IV-4.4.1: Impervious surface percentages in 187 upstream watersheds in Virginia coastal regions based on the RESAC impervious dataset in1990 and 2000.

Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)	Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)	Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)
1_M1_UP	0.4	0.69	32_M1_UP	0.63	1.2	21_B1_UP1	0	0.11
10_B1_UP	0.13	0.48	32_M2_UP	1.19	1.79	21_B1_UP2	0.29	0.4
10_M1_UP	0.3	0.71	33_M1_UP	6.48	7.97	21_B1_UP3	0.03	0.28
100_M1_UP	1.45	3.56	33_M2_UP	10.22	10.58	21_B1_UP4	0.51	1.11
11_M1_UP	1.29	4.39	33_M3_UP	3.88	5.1	21_B2_UP	0.18	0.96
12_M1_UP	1.98	3.53	33_M4_UP	2.53	3.17	21_M1_UP	0.13	0.39
13_B1_UP1	0.06	0.18	34_M1_UP	1.25	1.75	21_M2_UP	0.67	1.15
13_B1_UP2	0.08	0.51	34_M2_UP	0.22	0.7	22_M1_UP	0.21	0.99
13_B1_UP3	0.3	1.33	34_M3_UP	0.7	1.1	23_M1_UP	0.06	0.2
13_B1_UP4	0.58	1.11	35_B1_UP	0.07	0.14	23_M2_UP	0.07	0.25
13_M1_UP	0.1	0.33	35_B2_UP	0.15	0.31	23_M3_UP	0.08	0.31
14_M1_UP	0.09	0.44	35_M1_UP	0.35	0.76	24_M1_UP	0.09	0.29
15_B1_UP1	0	0.01	37_B1_UP1	0.54	1.3	25_M1_UP	0.21	0.67
15_B1_UP2	0.06	0.34	37_B1_UP2	0.03	0.26	25_M2_UP	0.12	0.47
15_B1_UP3	0.07	0.26	37_M1_UP	0.4	0.89	25A_M1_UP	0.34	1.02
15_B1_UP4	0	0.36	37_M2_UP	0.28	0.54	26_M1_UP	1.03	1.25
15_B1_UP5	0.04	0.43	39_M1_UP	0.52	1.36	26A_M1_UP	2.73	4.25
15_M1_UP	0.07	0.39	4_B1_UP	0.8	1.12	26A_M2_UP	0.13	0.55
16_B1_UP1	3.62	5.7	4_B2_UP	0.1	0.15	27_M1_UP	0.05	0.25
16_B1_UP2	1.53	2.34	4_M1_UP	0.22	0.43	28_M1_UP	0.13	0.5
16_B1_UP3	0.27	0.84	4_M2_UP	0.31	0.42	29_M1_UP	0.69	1.21
16_B2_UP	0	0.62	41_B1_UP	1.64	3.38	30_M1_UP	0.31	0.91
16_M1_UP	0.24	0.64	41_M1_UP	0.11	0.37	31_M1_UP	0.19	0.82
16_M2_UP	0.72	1.7	42_B1_UP	0.11	0.97	31_M2_UP	0.33	0.75
16_M3_UP	0.23	0.59	43_B1_UP1	0.87	1.57	46_M1_UP	1.79	3.22
1A_B1_UP	2.26	3.48	43_B1_UP2	0.03	0.12	46_M2_UP	0.6	2
1A_M1_UP	0.4	0.76	43_M1_UP	0.53	1	47_M1_UP	1.19	2.37
2_M1_UP	2.04	2.67	44_B1_UP1	1.48	2.49	47_M2_UP	0.19	0.45
2_M2_UP	0.51	0.75	44_B1_UP2	1.29	1.82	47A_M1_UP	0.61	0.98
20_M1_UP	0.66	1.28	44_B1_UP3	0.64	1.28	47A_M2_UP	0.18	0.45
20_M2_UP	1.56	2.6	44_M1_UP	0.56	0.9	47A_M3_UP	0.13	0.37
20_M3_UP	0.56	0.83	46_B1_UP	5.25	8.36	47A_M4_UP	0.24	0.59

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Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)	Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)	Subwatershed	Impervious 1990 (%)	Impervious 2000 (%)
49_M1_UP	0.25	0.6	48_M1_UP	0.14	0.47	81_M1_UP	0.55	2.25
5_B1_UP	0.22	0.39	48_M2_UP	0.16	0.5	81_M2_UP	0.12	0.69
5_M1_UP	0.23	0.34	61_B1_UP	2.93	3.71	82_B1_UP1	0.09	0.81
50_M1_UP	0.57	1.26	61_M1_UP	2.16	2.77	82_B1_UP2	0.08	0.5
50_M2_UP	0.18	0.42	62_M1_UP	1.09	1.84	82_M1_UP	0.16	0.77
50_M3_UP	1.85	2.59	63_M1_UP	3.14	5.56	84_M1_UP	0.71	1.99
50_M4_UP	0.48	0.78	63_M2_UP	6.38	13.81	85_B1_UP1	0.71	2.79
51_M1_UP	4.28	5.01	63_M3_UP	2.56	5.08	85_B1_UP2	2.07	4.06
51_M2_UP	3.27	4.73	7_B1_UP	0.32	0.69	85_B1_UP3	0.8	2.31
52_B1_UP	2.18	3.14	7_B3_UP	0.56	1.42	85_M1_UP	2.07	4.44
52_M1_UP	2.62	3.99	7_M1_UP	0.22	0.69	86_B1_UP1	0.61	1.38
53_B1_UP1	1.07	2.08	7_M2_UP	0.14	0.24	86_B1_UP2	0.78	1.44
53_B1_UP2	0.63	2.37	7_M3_UP	0.85	1.65	86_M1_UP	0.38	0.85
53_B1_UP3	3.99	6.51	70_M1_UP	29.5	31.38	86_M2_UP	0.34	1.34
53_B1_UP4	9.08	13.24	70_M2_UP	26.63	29.33	87_M1_UP	1.07	1.85
53_B1_UP5	4.85	7.55	73_M1_UP	19.59	21.95	88_B1_UP	2.72	6.61
53_B1_UP6	3.42	6.54	76_M1_UP	0.41	1.62	88_M1_UP	3.48	5.21
53_M1_UP	4.24	6.74	76_M2_UP	0.36	1.53	9_M1_UP	0.01	0.12
53_M2_UP	11.85	14.58	76_M3_UP	0.07	1.14	9_M2_UP	0.11	0.37
54_B1_UP1	20.17	20.71	77_M1_UP	0.53	2.09	9_M3_UP	0.05	0.24
54_B1_UP2	23.06	24.89	77_M2_UP	1.32	3.67	9_M4_UP	0.09	0.24
54_B2_UP1	10.88	16.01	77_M3_UP	0.89	2.43	90_M1_UP	1.52	4.84
54_B2_UP2	5.66	8.76	79_M1_UP	0.31	1.04	94_M1_UP	1.87	2.69
54_B2_UP3	13.78	17.39	8_B1_UP1	0.32	1.1	95_M1_UP	0.26	1.12
54_M1_UP	32.54	34.48	8_B1_UP2	0.01	0.34	97_M1_UP	0.94	3.1
58_M1_UP	16.54	21.29	8_B1_UP3	0.11	0.93	98_M1_UP	1.19	3.39
58_M2_UP	15.28	18.11	8_M1_UP	0.19	0.5	99_M1_UP	0.76	2.81
6_M1_UP	0.17	0.26	8_M2_UP	0.41	1.35			
6_M2_UP	0.17	0.32	8_M3_UP	1.75	2.58			
6_M3_UP	0.24	0.31	80_M1_UP	2.57	4.73			
60_M1_UP	0.45	0.72	80_M2_UP	0.18	0.79			
60_M2_UP	1.08	1.37	80_M3_UP	0.1	0.72			

Table IV-4.5.1: Sample sizes, calculated D values, and critical D values of five regions (Rappahannock River, York River, James River, Potomac River, and Eastern Shore) from Kolmogorov-Smirnov test. FC distributions in the five regions are significantly different from each other, with corresponding low p values ($p < 0.001$ in all pairs of) and greater D values than each of their critical values.

Dcritical / D	Rappahannock	York	James	Eastern Shore	Potomac
Rappahannock	**15504**	0.016651	0.016751	0.016193	0.015931
York	0.068343	**11710**	0.017868	0.017346	0.017101
James	0.11921	0.051909	**11466**	0.017442	0.017199
Eastern Shore	0.07691	0.12123	0.16855	**12941**	0.016656
Potomac	0.032862	0.081923	0.13255	0.067801	**13752**

Note: The numbers in blue cells are the sample size for each region. The values on upper right side are the critical values, and the values on lower left side are calculated D values for each pair of regions.

Table IV-4.5.2: The grouping of 107 upstream watersheds into 4 regions: Rappahannock River, York River, James River, and the Eastern Shore.

Region	Watershed	Region	Watershed	Region	Watershed	Region	Watershed
Rappahanock River	20_M1_UP	The Eastern shore	76_M1_UP	The James river	58_M1_UP	The York river	46_B1_UP
	20_M2_UP		76_M2_UP		58_M2_UP		46_M1_UP
	20_M3_UP		76_M3_UP		60_M1_UP		46_M2_UP
	21_B1_UP1		77_M1_UP		60_M2_UP		47_M1_UP
	21_B1_UP2		77_M2_UP		61_B1_UP		47_M2_UP
	21_B1_UP3		77_M3_UP		61_M1_UP		47A_M1_UP
	21_B1_UP4		79_M1_UP		62_M1_UP		47A_M2_UP
	21_B2_UP		80_M1_UP		63_M1_UP		47A_M3_UP
	21_M1_UP		80_M2_UP		63_M2_UP		47A_M4_UP
	21_M2_UP		80_M3_UP		63_M3_UP		48_M1_UP
	22_M1_UP		81_M1_UP		70_M1_UP		48_M2_UP
	23_M1_UP		81_M2_UP		70_M2_UP		49_M1_UP
	23_M2_UP		82_B1_UP1		73_M1_UP		50_M1_UP
	23_M3_UP		82_B1_UP2				50_M2_UP
	24_M1_UP		82_M1_UP				50_M3_UP
	25_M1_UP		84_M1_UP				50_M4_UP
	25_M2_UP		85_B1_UP1				51_M1_UP
	25A_M1_UP		85_B1_UP2				51_M2_UP
	26_M1_UP		85_B1_UP3				52_B1_UP
	26A_M1_UP		85_M1_UP				52_M1_UP
	26A_M2_UP		86_B1_UP1				53_B1_UP1
	27_M1_UP		86_B1_UP2				53_B1_UP2
	28_M1_UP		86_M1_UP				53_B1_UP3
	29_M1_UP		86_M2_UP				53_B1_UP4
	30_M1_UP		87_M1_UP				53_B1_UP5
	31_M1_UP		88_B1_UP				53_B1_UP6
	31_M2_UP		88_M1_UP				53_M1_UP
	32_M1_UP		90_M1_UP				53_M2_UP
	32_M2_UP		94_M1_UP				
	33_M1_UP		95_M1_UP				
	33_M2_UP		97_M1_UP				
	33_M3_UP		98_M1_UP				
	33_M4_UP		99_M1_UP				

Table IV-4.5.3: Eigenvectors of environmental variables for the first 5 principal components based on Principal Component Analysis on 107 upstream watersheds located in the Rappahannock River, York River, James River, and Eastern Shore regions.

Variable	PC1	PC2	PC3	PC4	PC5
Slope	-0.492	-0.172	0.442	-0.243	-0.27
Drainage density	-0.007	0.044	-0.027	0.019	0.005
Eccentricity	0.034	-0.006	0.005	0.223	0.099
Urban	-0.087	0.459	-0.366	-0.467	-0.1
Forest	-0.437	-0.365	0.109	0.075	0.355
Pasture	0.561	-0.041	0.414	-0.336	-0.173
Agriculture	0.388	-0.074	0.135	0.504	-0.046
Wetland	-0.055	0.07	-0.175	0.323	-0.252
Water area	-0.131	0.6	0.267	0.13	-0.062
Ratio	-0.107	-0.21	-0.019	0.061	-0.769
Residence time	0.009	0.065	0.136	-0.096	0.275
Water Volume	-0.079	0.322	0.166	0.098	0.025
Watershed area	-0.172	0.305	0.429	0.281	-0.012
Runoff potential	0.156	-0.088	0.369	-0.279	0.117

Table IV-4.5.4: Eigenvectors of environmental variables for the first 5 principal components based on Principal Component Analysis on 94 upstream watersheds located in the Rappahannock River, York River, and Eastern Shore regions.

Variable	PC1	PC2	PC3	PC4	PC5
Slope	-0.492	0.289	0.509	0.309	0.215
Drainage density	-0.017	-0.493	0.218	0.035	0.191
Eccentricity	0.036	-0.01	-0.101	-0.258	0.782
Urban	-0.045	-0.589	0.305	0.059	-0.02
Forest	-0.47	0.227	-0.27	0.019	-0.076
Pasture	0.55	0.33	0.327	0.214	-0.207
Agriculture	0.388	0.14	-0.102	-0.205	0.243
Wetland	-0.06	0.019	-0.175	-0.096	0.089
Water area	-0.075	0.07	0.187	-0.419	-0.15
Ratio	-0.115	0.179	-0.001	0.229	0.127
Residence time	0.022	-0.133	0.326	-0.09	-0.063
Water Volume	-0.041	0.024	0.13	-0.227	-0.064
Watershed area	-0.152	0.188	0.312	-0.662	-0.132
Runoff potential	0.149	0.234	0.338	0.095	0.356

Table IV-4.6.1: The linear regressions equation, as well as p-value and R square values, showing the relationships between FC concentrations with rainfall intensities for each 7 days before sampling dates.

Days before sampling date	Regression Equation	P-value	R-Square
1	FC = 37.3 + 108 Day1	<0.0001	4.80%
2	FC = 45.5 + 40.6 Day2	<0.0001	0.70%
3	FC = 46.8 + 26.2 Day3	<0.0001	0.30%
4	FC = 49.1 +6.77 Day4	<0.0001	0.00%
5	FC = 49.4 +5.23 Day5	<0.0001	0.00%
6	FC = 49.8 +1.72 Day6	<0.0001	0.00%
7	FC = 49.3 +5.58 Day7	<0.0001	0.00%

Table IV-4.7.1: Leaf report based on CART analysis on 165 upstream watersheds in Virginia coastal regions, in order to demonstrate the relationship between environmental variables and fecal contamination levels, indicated by FC mean concentration.

Leaf Report

Leaf Label	FC Mean concentration (MPN/100ml)	Count
Ratio < 76.35 & Runoff Potential < 0.034 & Forest >= 0.49	6.3587724	7
Ratio < 76.35 & Runoff Potential < 0.034 & Forest < 0.49	22.086686	5
Ratio < 76.35 & Runoff Potential >= 0.034 & Impervious 1990 < 0.0065 & Pature <0.066	14.26138	9
Ratio < 76.35 & Runoff Potential >= 0.034 & Impervious 1990 < 0.0065 & Pature >=0.066	22.084475	69
Ratio < 76.35 & Runoff Potential >= 0.034 & Impervious 1990 >= 0.0065 & Wetland <0.053	22.28672	36
Ratio < 76.35 & Runoff Potential >= 0.034 & Impervious 1990 >= 0.0065 & Wetland >=0.053 & Residence Time < 0.56	20.512921	6
Ratio < 76.35 & Runoff Potential >= 0.034 & Impervious 1990 >= 0.0065 & Wetland >=0.053 & Residence Time >= 0.56	37.807975	13
Ratio >= 76.35	30.093153	20

Note : leaf label shows there are 8 leafs; each leaf represents one condition of matching watersheds. The count indicates how many upstream watersheds match the condition.

Table V-2.1: Runoff coefficients for pervious and impervious surfaces in warm and cold seasons based on values in the Manuals and Reports of Engineering (1992) from the American Society of Civil Engineers.

Land Cover	Season	Pervious	Impervious
Urban	warm	0.4	0.9
	cold	0.5	0.9
Forest	warm	0.15	0.8
	cold	0.2	0.8
Crop-pasture	warm	0.25	0.8
	cold	0.35	0.8

Table V-3.1. FCMCs derived based on categorized watersheds using Group 2 (which has 56 watersheds) as an example. The value of coefficient for each variable is the value of FCMC for each type of land cover. Pasture has a negative value.

Regression Statistics								
Multiple R	0.7549							
R Square	0.5699							
Adjusted R Square	0.5241							
Standard Error	6.56E+10							
Observation	53							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	5	2.68E+23	5.36E+22	12.4531	1.02E-07			
Residual	47	2.02E+23	4.30E+21					
Total	52	4.70E+23						
	Coefficients (FCMC)	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.56E+09	1.24E+10	0.13	0.90	-2.34E+10	2.65E+10	-2.34E+10	2.65E+10
Urban	3.16E+05	2.82E+05	1.12	0.27	-2.52E+05	8.84E+05	-2.52E+05	8.84E+05
Cropland	4.74E+05	2.48E+05	1.91	0.06	-2.51E+04	9.73E+05	-2.51E+04	9.73E+05
Forrest	2.83E+04	1.23E+05	0.23	0.82	-2.20E+05	2.76E+05	-2.20E+05	2.76E+05
Pasture	-7.33E+05	7.98E+05	-0.92	0.36	-2.34E+06	8.72E+05	-2.34E+06	8.72E+05
Wetland	5.89E+05	5.13E+05	1.15	0.26	-4.44E+05	1.62E+06	-4.44E+05	1.62E+06

Table V-3.2: FCMCs and their standard deviation for different land covers derived from single-land-cover-dominated watersheds.

Land Cover	Season	Watershed	FCMC (MPN/M2*INCH)	Mean (MPN/M2*INCH)	Standard deviation
Crop-Pasture	Warm	8_B1_UP3	2.30E+05	2.09E+05	9.17E+04
		8_M3_UP	1.75E+06		
		82_B1_UP2	1.87E+05		
		88_M1_UP	1.36E+05		
	Cold	8_B1_UP3	9.17E+04	5.62E+04	1.95E+04
		8_M3_UP	3.55E+05		
		82_B1_UP2	3.39E+04		
		88_M1_UP	1.96E+04		
Forest	Warm	13_B1_UP1	4.80E+04	1.17E+05	4.64E+04
		13_B1_UP2	1.34E+05		
		21_B1_UP1	1.36E+05		
		27_M1_UP	1.50E+05		
	Cold	13_B1_UP1	4.41E+04	5.06E+04	2.57E+04
		13_B1_UP2	8.86E+04		
		21_B1_UP1	3.71E+04		
		27_M1_UP	3.28E+04		
Urban	Warm	54_B1_UP2	1.45E+05	1.63E+05	1.88E+05
		54_M1_UP	8.82E+04		
		70_M1_UP	1.97E+05		
		70_M2_UP	2.23E+05		
	Cold	54_B1_UP2	1.26E+05	1.14E+05	1.32E+05
		54_M1_UP	6.04E+04		
		70_M1_UP	8.43E+04		
		70_M2_UP	1.85E+05		

Note: The value shown in red is one or two orders of magnitude higher than other values. It was not used in the calculation of mean and standard deviation.

Table V-3.3. Comparison of FCMCs between this study and previous studies. The units of FCMC from previous studies were converted to the same unit used in this study. Previous studies didn't separate FC loading into seasons and research sites are located in different states. The sites in Reinelt and Horner, (1995) are in Washington state and the study sites from Weiskel et al., (1996) are located in Massachusetts.

Land condition	Total loading	Unit	Additional information	Converted total loading (FC m^{-2} $inch^{-1}$)	Sources
From this study:					
Crop-Pastureland (Warm)	152903.14	FC m^{-2} $inch^{-1}$		1.5×10^5	
Crop-Pastureland (Cold)	37838.09	FC m^{-2} $inch^{-1}$		3.8×10^4	
Forest(Warm)	116814.55	FC m^{-2} $inch^{-1}$		1.2×10^5	
Forest(Cold)	50627.00	FC m^{-2} $inch^{-1}$		5.1×10^4	
Urban (Warm)	163282.84	FC m^{-2} $inch^{-1}$		1.6×10^5	
Urban (Cold)	113879.28	FC m^{-2} $inch^{-1}$		1.1×10^5	
Previous studies:					
Urban	4.2×10^{10}	FC ha^{-1} $year^{-1}$	Annual precipitation 34.78 inches	1.2×10^5	Reinelt and Horner, 1995
Nonurban	1.4×10^9	FC ha^{-1} $year^{-1}$		4.0×10^3	Reinelt and Horner, 1995
Low intensity land use	$1.0 \times 10^{10.06}$	FC cm^{-1} of rain	Land area: 28.32 km^2	1.0×10^3	Weiskel et al., 1996
Moderate-density residential, impervious surfaces	$1.0 \times 10^{10.2}$	FC cm^{-1} of rain	Land area: 0.032 km^2	1.3×10^6	Weiskel et al., 1996
High-density residential, impervious surfaces	$1.0 \times 10^{10.9}$	FC cm^{-1} of rain	Land area: 0.029 km^2	6.9×10^6	Weiskel et al., 1996
Commercial, impervious surfaces	$1.0 \times 10^{9.4}$	FC cm^{-1} of rain	Land area: 0.020 km^2	3.2×10^5	Weiskel et al., 1996

Table V-3.4. Selected watersheds and their major land cover change from 1984 to 2005 in percentage (%) based on the RESAC impervious dataset in 1990 and 2005.

Watershed	Urban	Cropland	Pastureland	Forest	Wetland
52_M1_UP	34.95	-0.37	-11.05	-22.32	-1.40
58_M1_UP	39.93	-11.45	-7.18	-21.62	-1.02
58_M2_UP	25.49	-3.84	-7.46	-14.43	-0.88
63_M2_UP	27.44	-4.70	-15.59	-7.18	-0.90

Table V-4.1. Sensitivity test with parameters changing by $\pm$ 20 percent. Four parameters (pervious area runoff coefficient, impervious area runoff coefficient, return ratio in one tidal cycle, and fecal bacteria decay rate in the water) were adjusted by ±20% to see how much change the output values (FCMC values) would undergo.

Land Cover	Season	FC decay ratio (%)	Return ratio (%)	Pervious runoff coefficient (%)	Impervious runoff coefficient (%)
Crop-Pasture	Warm	12.50	5.25	19.86	0.86
	Cold	15.00	5.19	20.47	0.32
Forest	Warm	13.88	4.96	20.77	0.05
	Cold	15.75	5.38	20.79	0.04
Urban	Warm	13.43	5.20	10.34	10.61
	Cold	15.27	5.29	11.48	8.74

FIGURES

Figure IV-2.1.1: Study Sites in Virginia Coastal Plain in Lower Chesapeake Bay

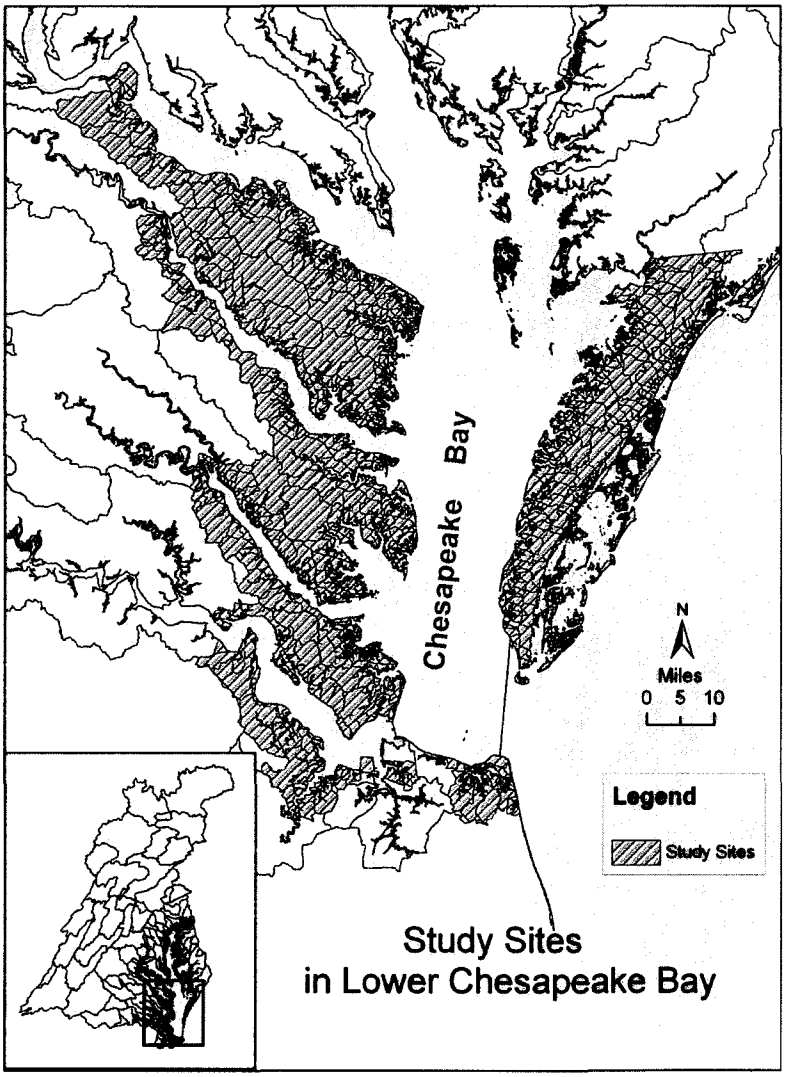


Figure IV-3.1.1: Tidal levels coded into 9 groups by DSS. These codes are: 1 (high tide-1.4 hours ebb), 2 (1.5 hours ebb-2.9 hours ebb), 3 (3.0 hours ebb-4.4 hours ebb), 4 (4.5 hours Ebb-low tide), 5(Low tide - 1.4 hours flood), 6(1.5 hours flood-2.9 hours flood), 7(3.0 hours flood-4.4 hours flood), 8(4.5 hours flood-high tide), 9(no data).

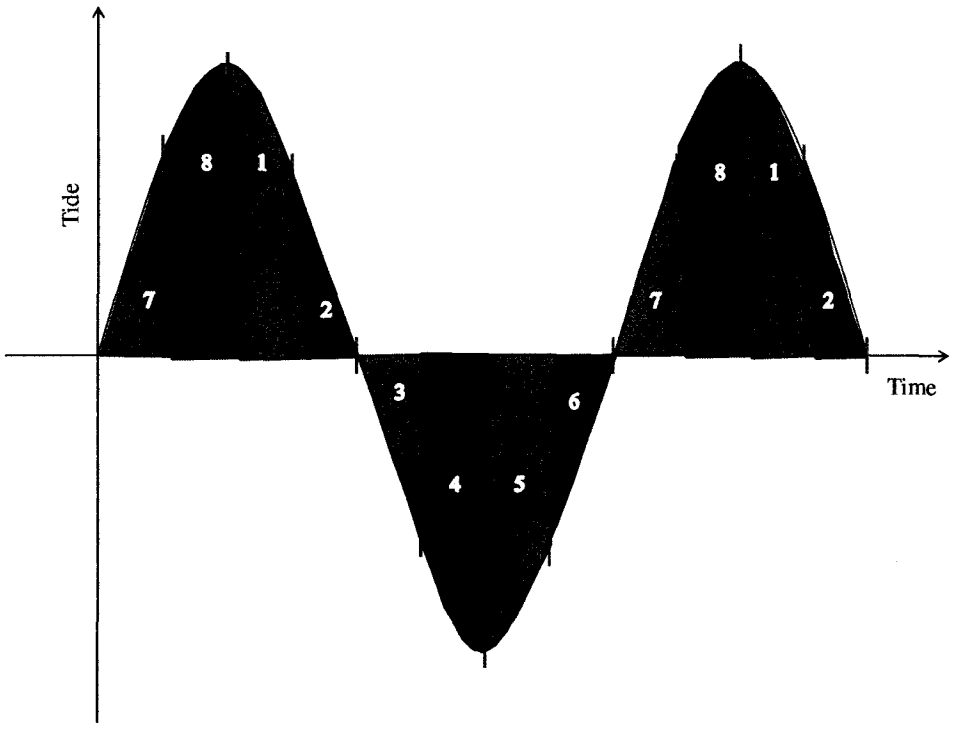


Figure IV-4.1.1: 392 FC monitoring stations that have tidal information collected along with FC data by DSS.

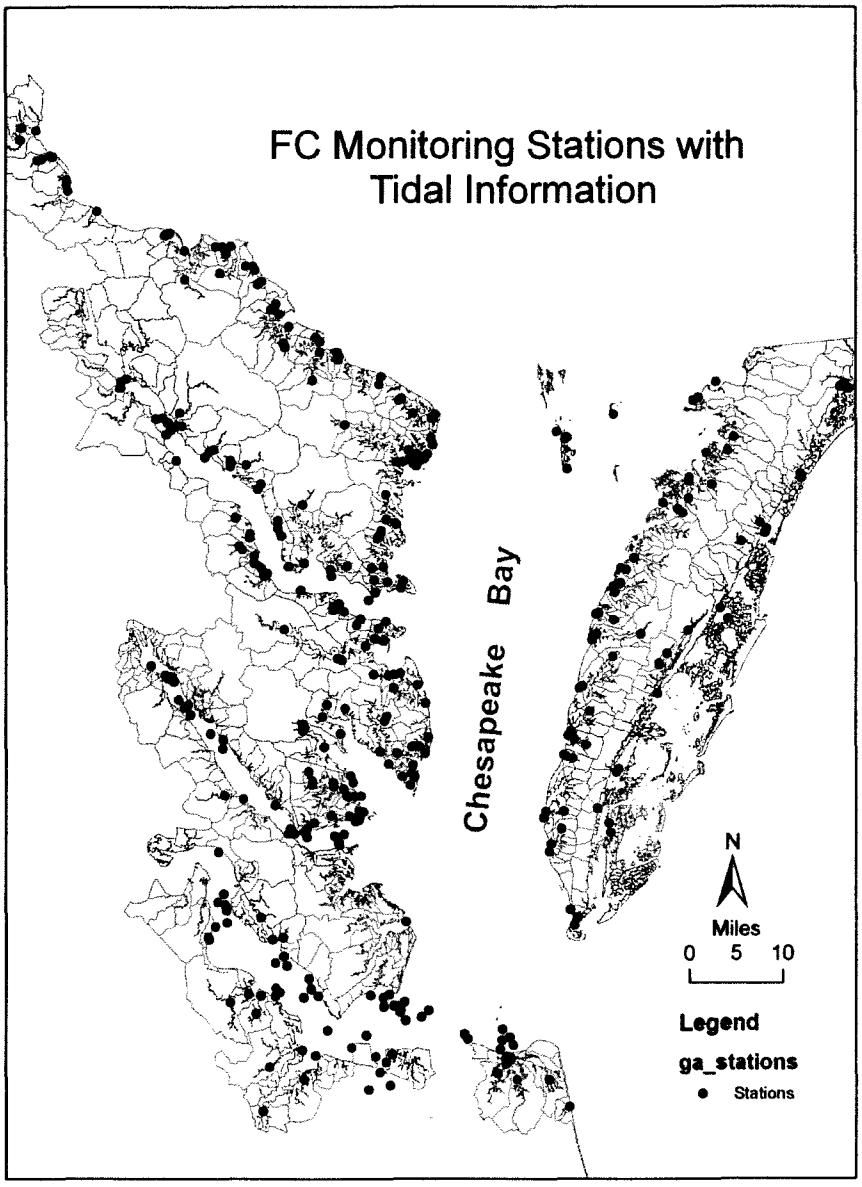


Figure IV-4.1.2: Comparison of FC concentration difference due to the effects from seasons and tides. The seasonal difference between winter FC concentration (January to March) and summer FC concentration (July to September) is 18.04 MPN/100ml as the median value, with the first quartile equaling 7.31 MPN/100ml and third quartile equaling 41.76 MPN/100ml. The tidal difference is 0.17 MPN/100ml as the median value, with the first quartile equaling -1.17 MPN/100ml and third quartile equaling 7.05 MPN/100ml. The difference caused by tides is much smaller than the difference caused by seasons.

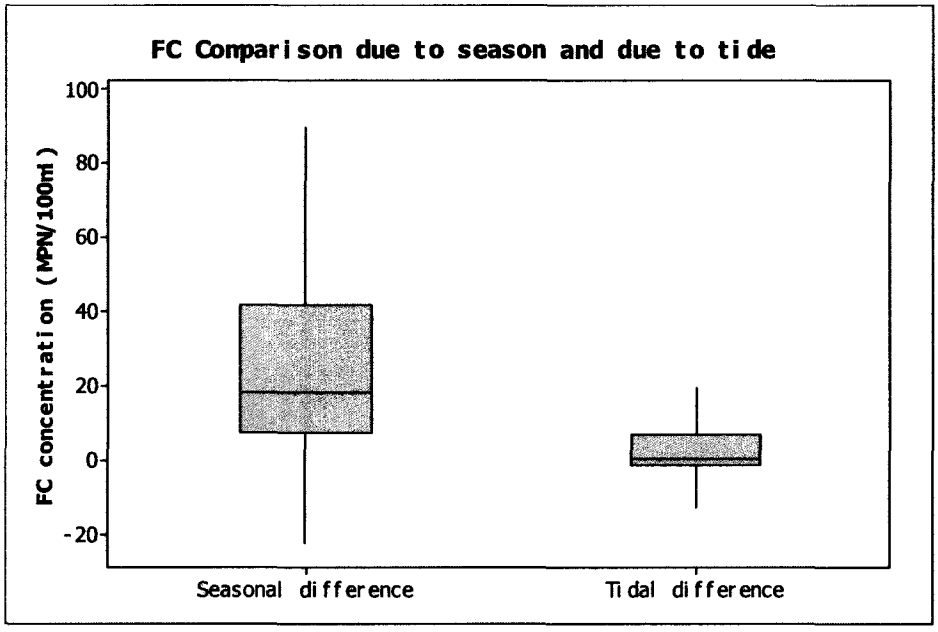
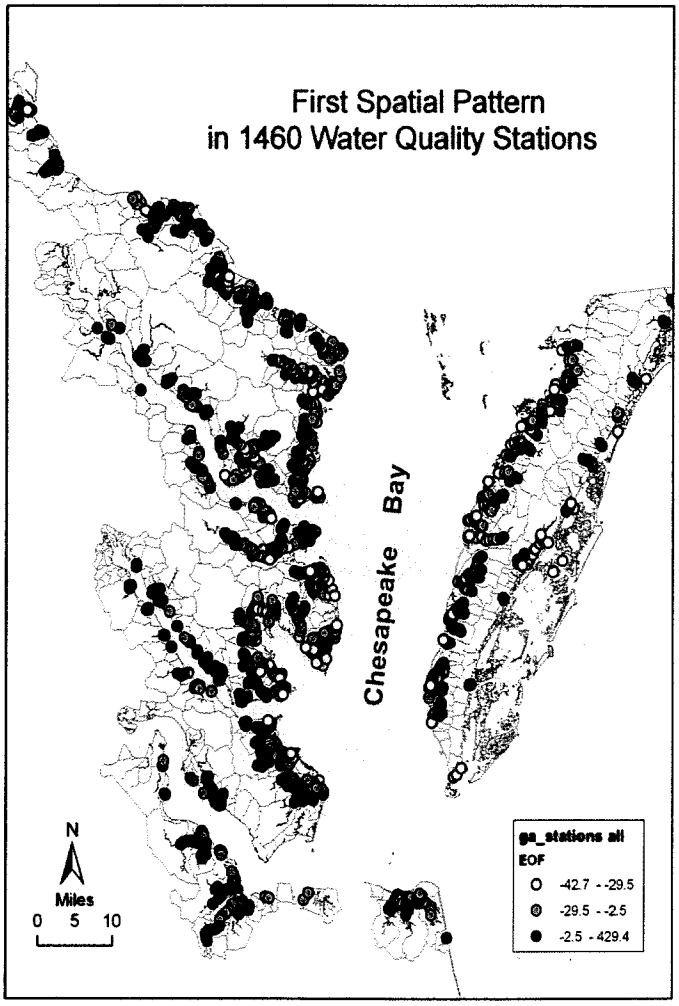


Figure IV- 4.2.1.: Map of first spatial component from EOF methods applied to the data matrix of 1460 stations x 12 months. Figure a demonstrates that there was a consistent spatial pattern in almost in every embayment, with high spatial component values in upstream areas, and decreasing values downstream. Figure b shows the eigenvalues in red and cumulated variation in purple. The first component explained about 78% of data variation. Figure c shows the first temporal component with positive values, indicating that the first spatial pattern was consistent within the months, but varied in magnitude between the months.

a)



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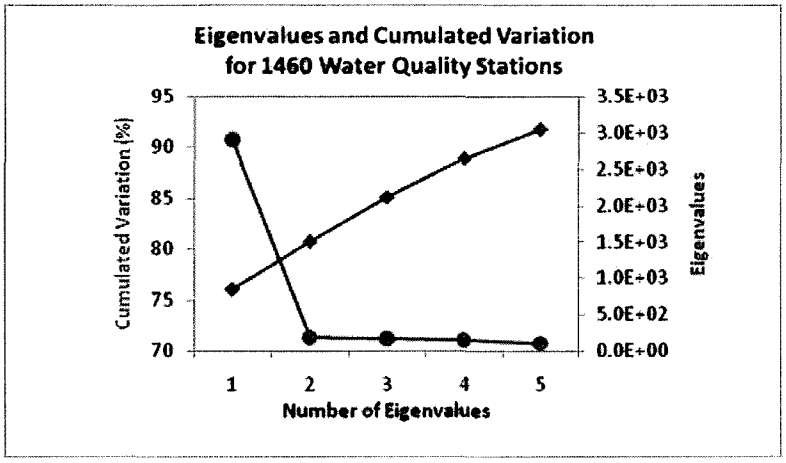
b)



c)

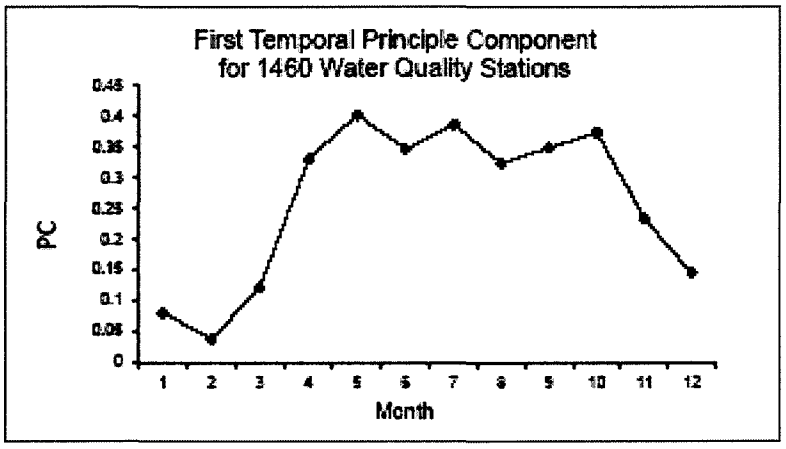


Figure IV-4.2.2: DSS stations were evenly separated into 3 groups according to their first spatial component values. Red dots represent high spatial component values, which indicate areas of relatively high fecal contamination levels, yellow are medium values and green are low values. High fecal contamination levels are almost all located in headwater regions. The stations in red are called upstream stations, yellow stations are middlestream stations and green ones are downstream stations.

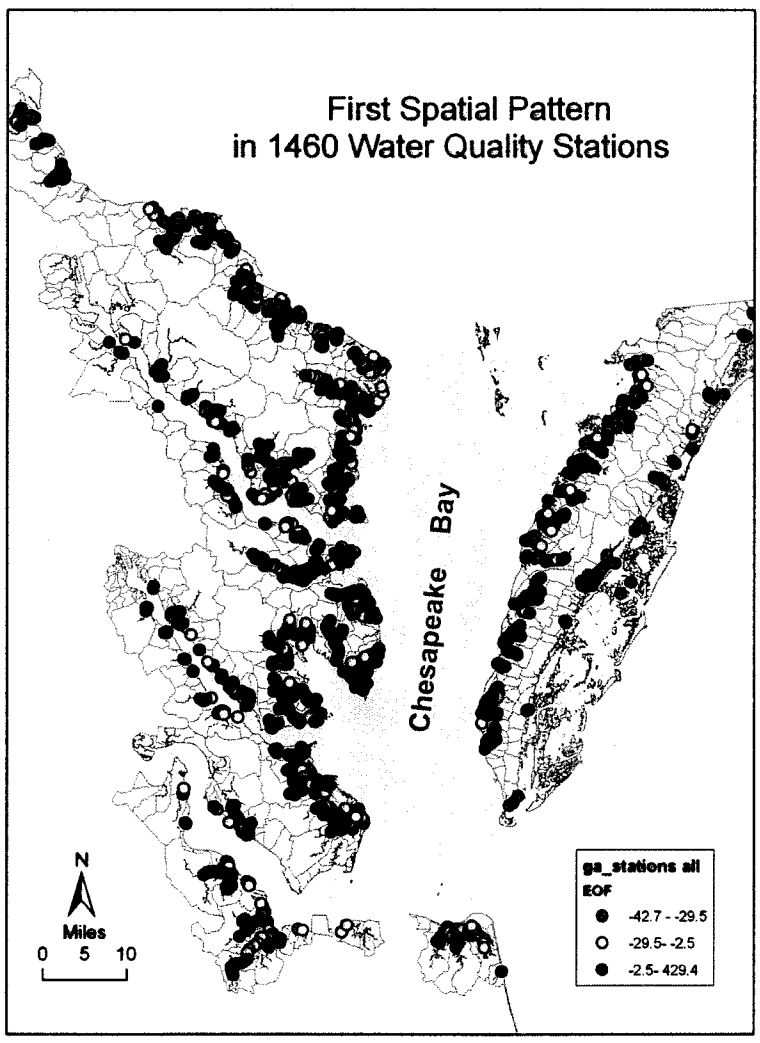


Figure IV-4.2.3: FC Concentration Frequency Distribution in upstream, uiddlestream, and downstream stations. Highest FC concentrations appear most frequently in upstream regions, occur less frequently in the middlestream, and lowest occurs in downstream.

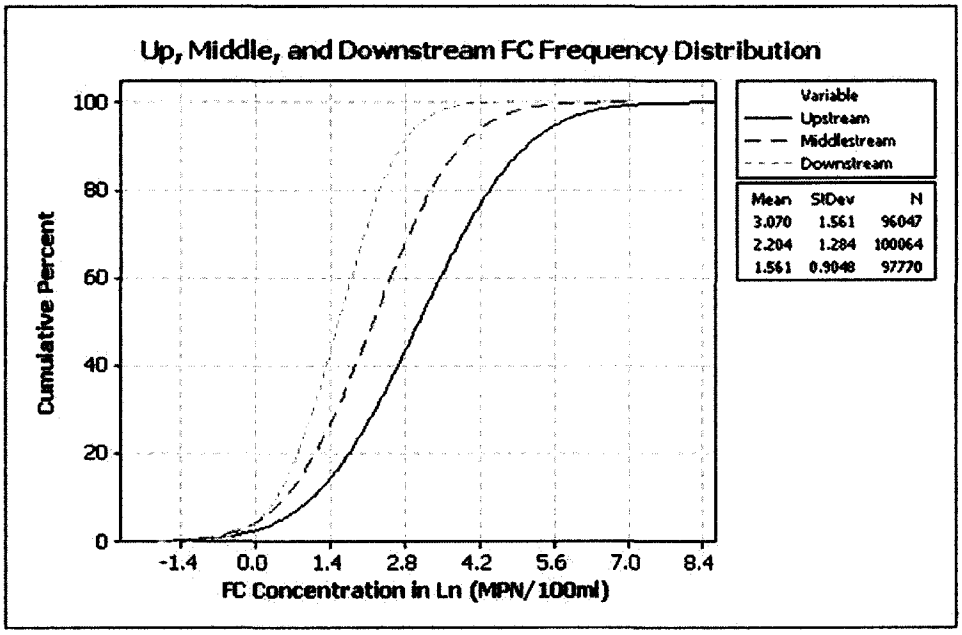


Figure IV-4.2.4: Upstream watersheds in Virginia coastal area. The watersheds surrounding upstream stations were called upstream watersheds. There are a total of 187 upstream watersheds. Most analyses in this study were conducted on these upstream stations and upstream watersheds, shown as pink areas.

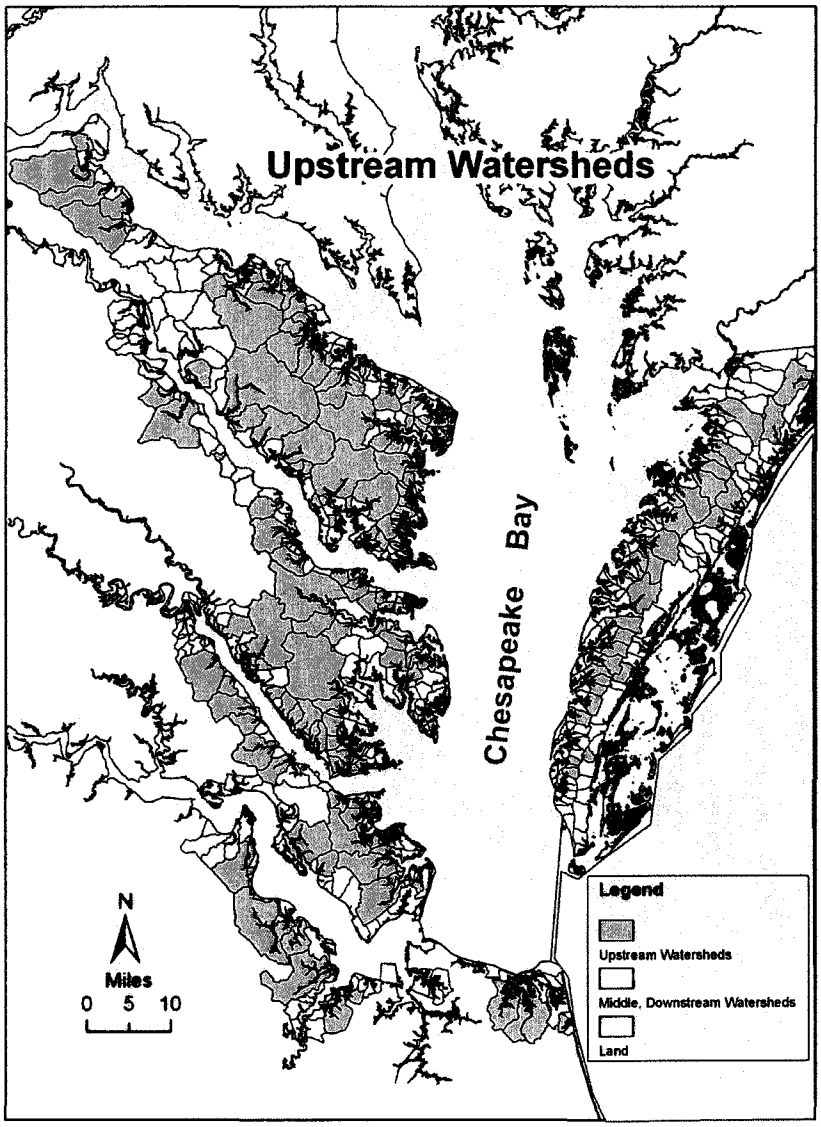


Figure IV-4.3.1: The locations of selected upstream watersheds dominated by a single land cover. In a watershed, if forest, urban, or crop and pastureland together occupy more than 80%, 70%, or 70%, respectively, this watershed was called single land-cover-dominated. Here crop and pastureland were combined together, since neither one consisted of more than 60% of the total area of any watershed.

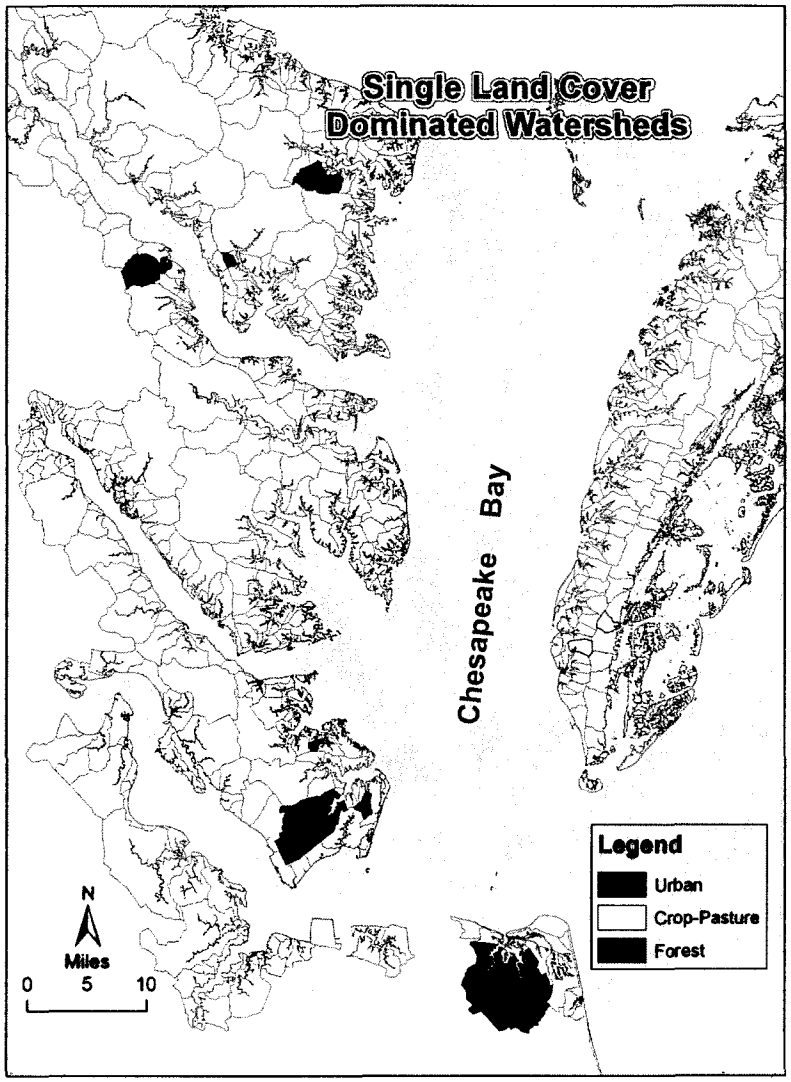


Figure IV-4.3.2: FC Frequency Distribution in the receiving waters of crop-pastureland, forest, and urban-dominated upstream watersheds. FC monitoring stations located in each watershed were grouped together. Green curve represents cumulative frequency distribution in urban-dominated watersheds, black is crop-pastureland-dominated watersheds, and red is forest-dominated watersheds. The figure shows that the highest FC concentrations occur most frequently in urban-dominated waters, with lower concentrations in crop-pastureland-dominated waters and forest-dominated waters.

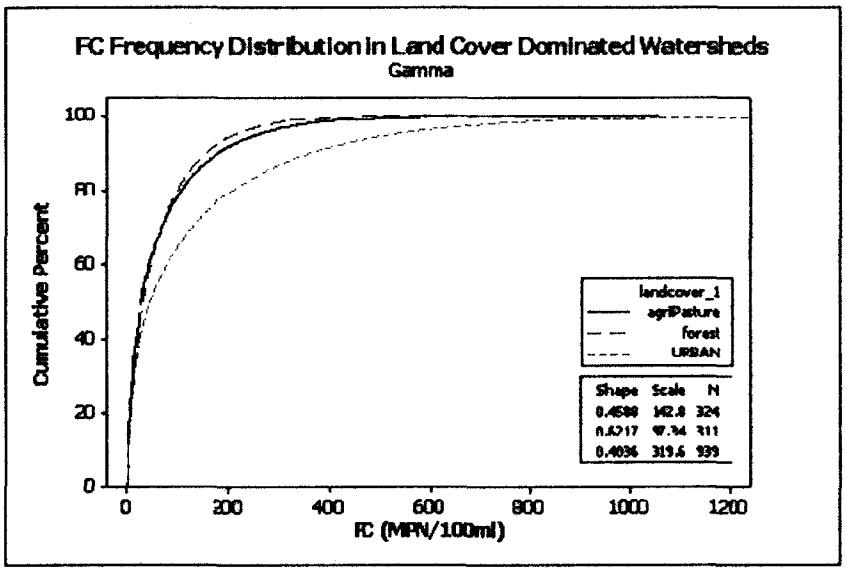
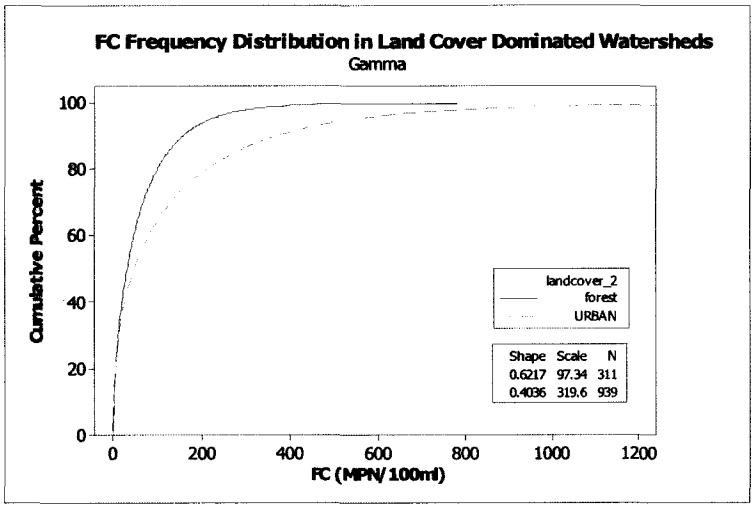


Figure IV-4.3.3. FC Frequency Distribution in forest and urban-dominated upstream watersheds and their Monthly FC Frequency Distribution.



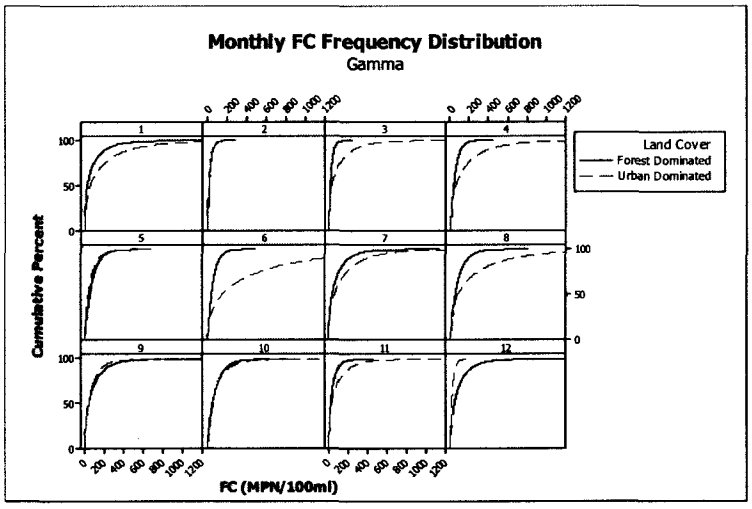


Figure IV-4.4.1: Cumulative probability curves resulting from a nonparametric changepoint analysis show FC geometric means in response to percent impervious surface covers in the years 1990 and 2000. The method showed that the potential impervious percentage threshold was about 14% in 1990 and around 18% in 2000, with low p values.

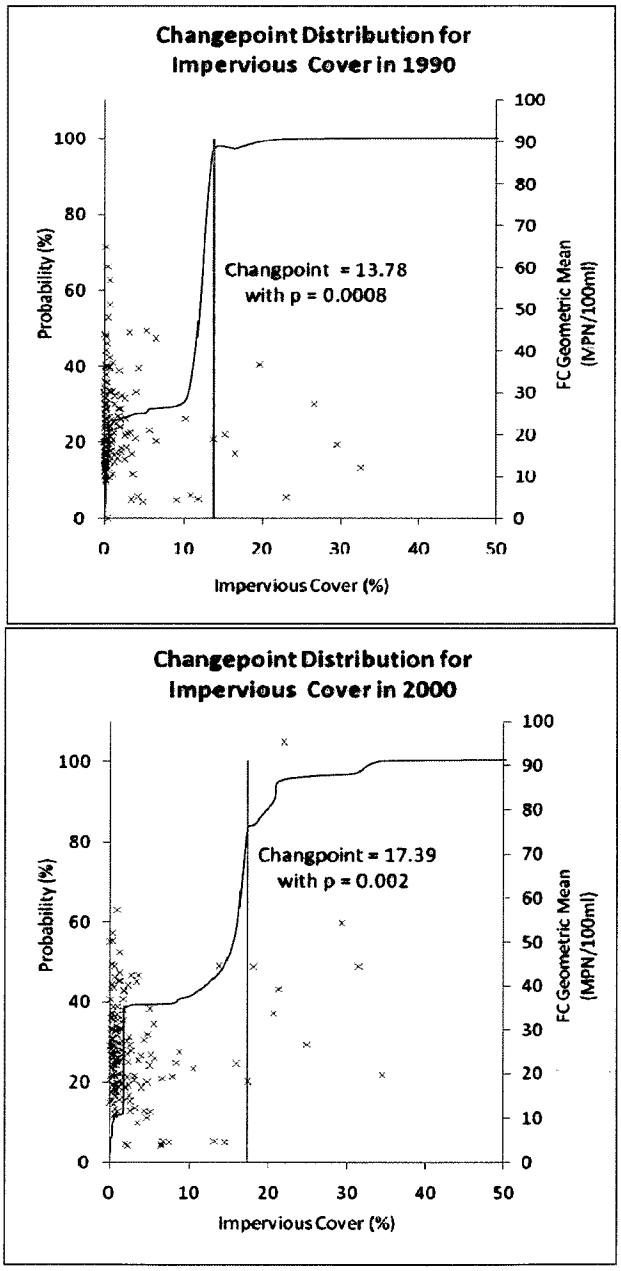
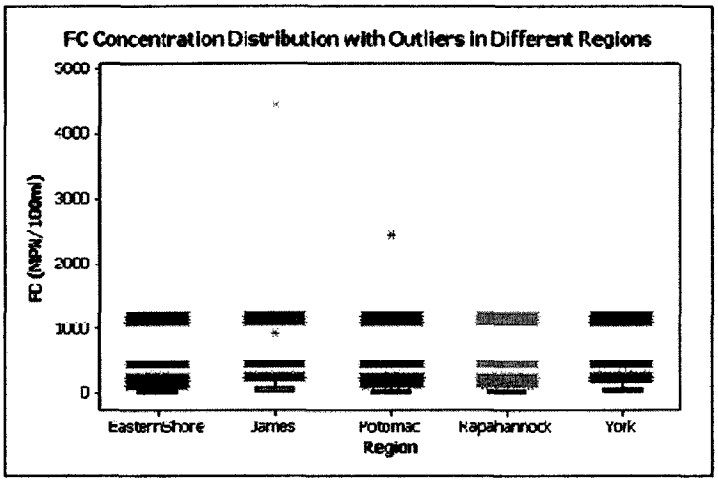
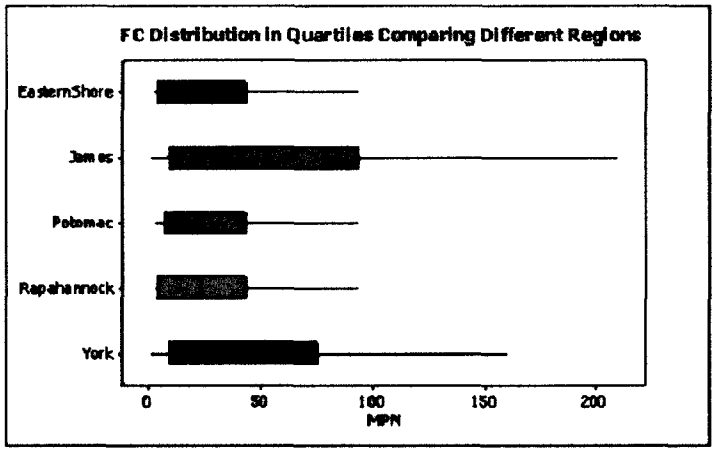


Figure IV-4.5.1: FC Concentration Distribution with and without outliers in different regions. Their distributions are significantly different from each other with $p < 0.001$ from K-S test.

a) With outliers and all values



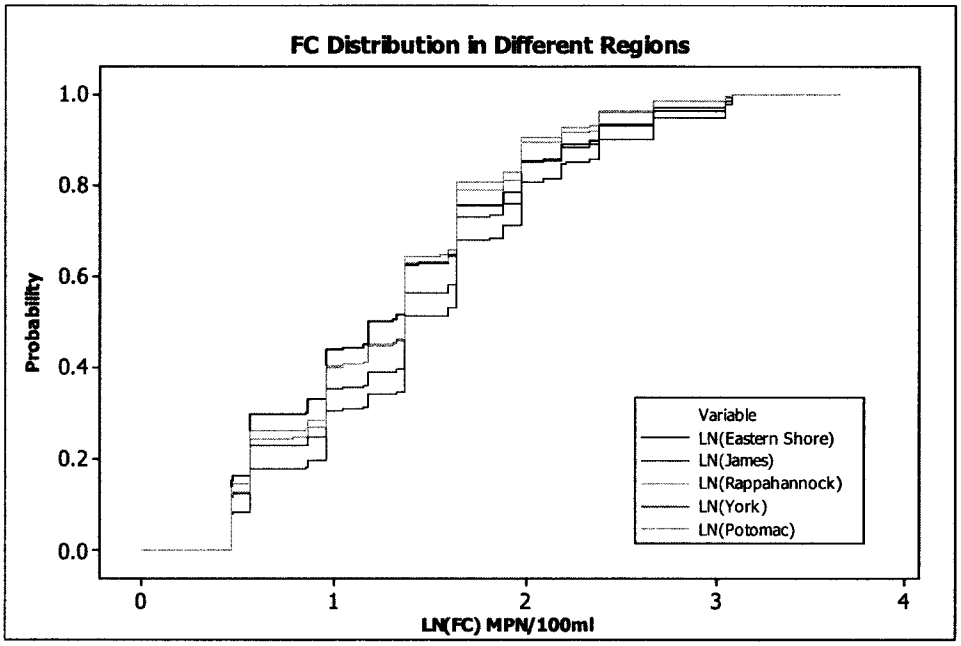
b) Without outliers and only plotting values <200 MPN/100ml



Note: e: Eastern Shore
p: Potomac River
y: York river
j: James River
r: Rappahannock River

Figure IV-4.5.2: Comparison of FC Concentration Frequency Distributions in different regions. a) All FC distributions in different regions on one graph; b) Pair comparison of FC distributions in different regions.

a) All FC distributions in different regions on one graph



b) Pair comparison of FC distributions in different regions.

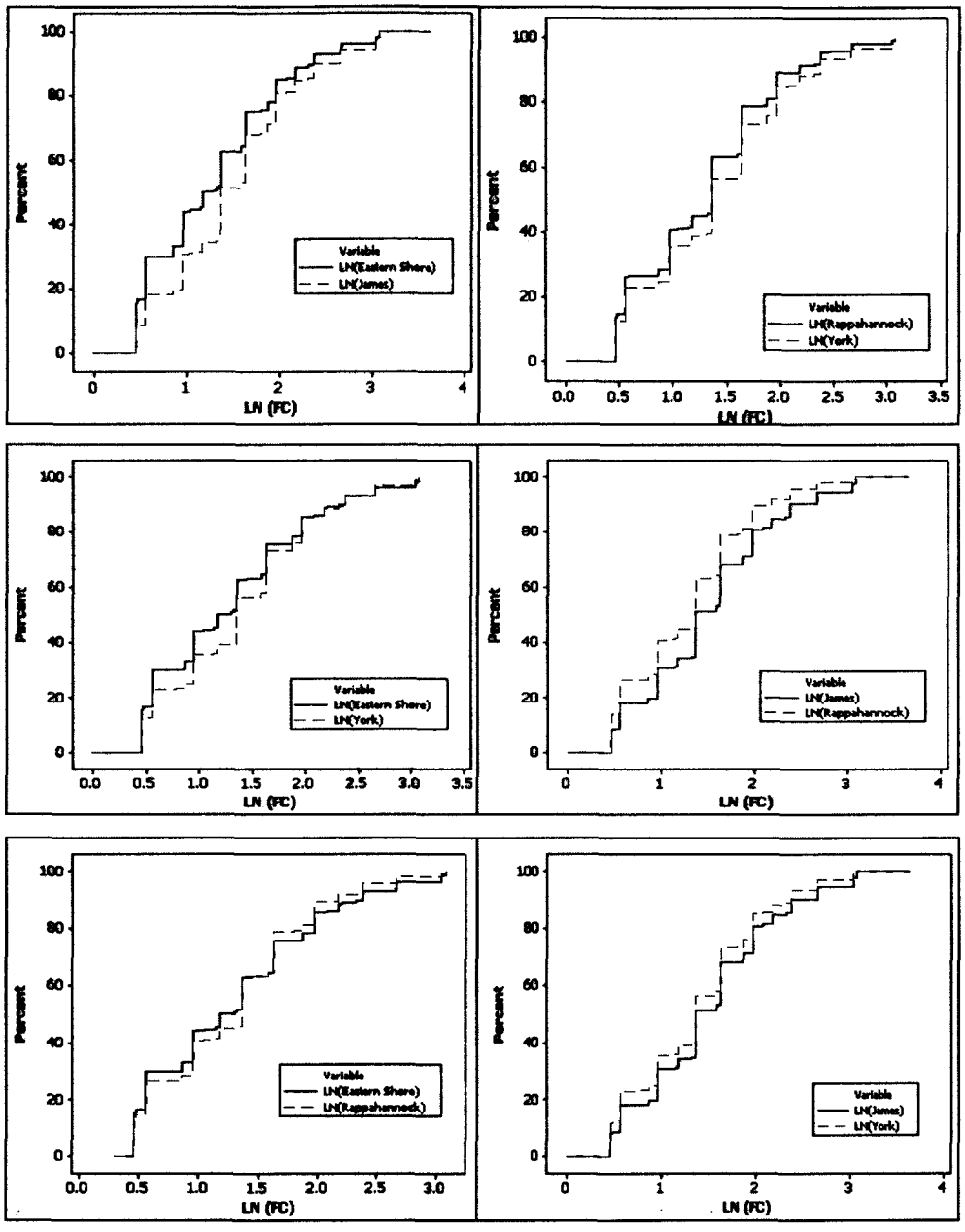
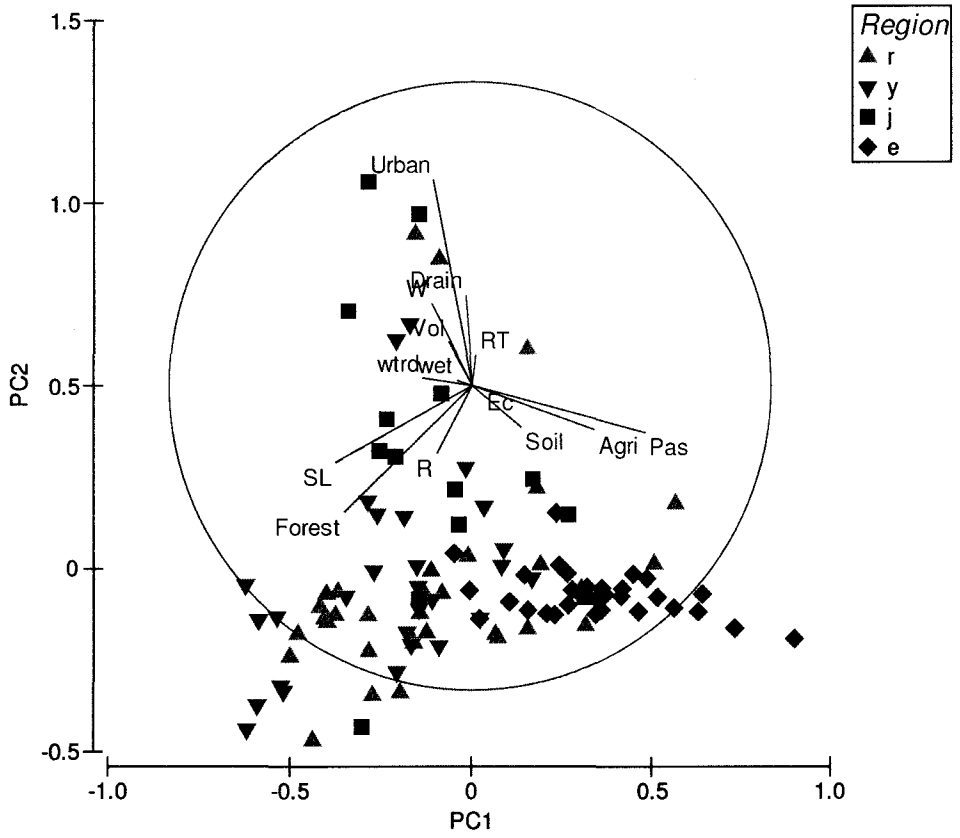


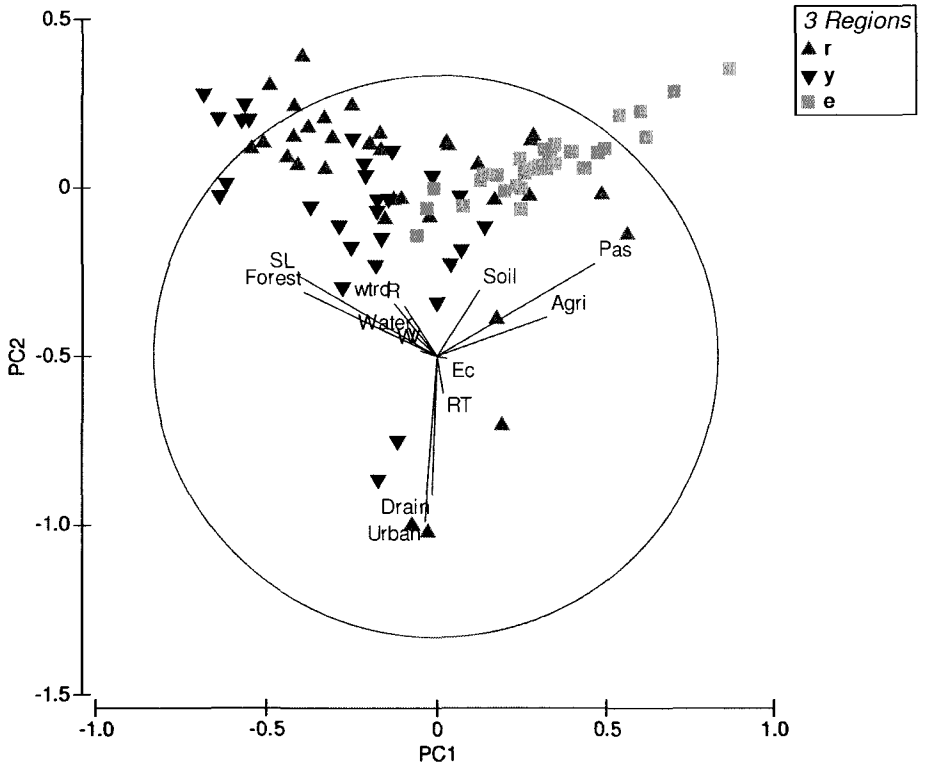
Figure IV-4.5.3: PCA plot based on environmental variables from Rappahannock River, York River, James River, and Eastern Shore regions. PCA analysis on 107 upstream watersheds showed that the first principal component accounts for 30.2% of the variability and the second component accounts for 21.8% of the variability (cumulatively 52%).



Note: Region: r: = Rappahannock River
y =York River
j = James River
e = Eastern Shore

Variables: Drain = Drainage density
W = Water area
wtrd = Watershed area
wet = Wetland percentage
RT = Residence time
EC = Eccentricity
Soil = Runoff potential
Vol = Water volume
Pas = Pastureland percentage
Agri = Cropland percentage
Forest = Forest percentage
Urban = Urban percentage
SL = slope
R = Ratio of water area divided by watershed area

Figure IV-4.5.4: PCA plot based on environmental variables from Rappahannock River, York River, and Eastern Shore regions. PCA analysis showed that the first PC explains 47% of data variation, with 12.6% for the second PC (cumulatively 59.6%).



Note: Region: r = Rappahannock River
y = York River
e = Eastern Shore

Variables: Drain = Drainage density
wtrd = Watershed area
RT = Residence time
Soil = Runoff potential
Pas = Pastureland percentage
Forest = Forest percentage
SL = slope
R = Ratio of watershed area divided by water area
W = Water area
wet = Wetland percentage
EC = Eccentricity
Vol = Water volume
Agri = Cropland percentage
Urban = Urban percentage

Figure IV-4.6.1: Comparison of annual precipitation and FC geometric mean concentrations from 1985 to 1998 in Virginia coastal regions. The Chesapeake Bay Program watershed model (Phase V) provides hourly rainfall data for the period from 1/1/1985 to 12/31/1998. Annual rainfall data were obtained by summing all the hourly rainfall records of each year.

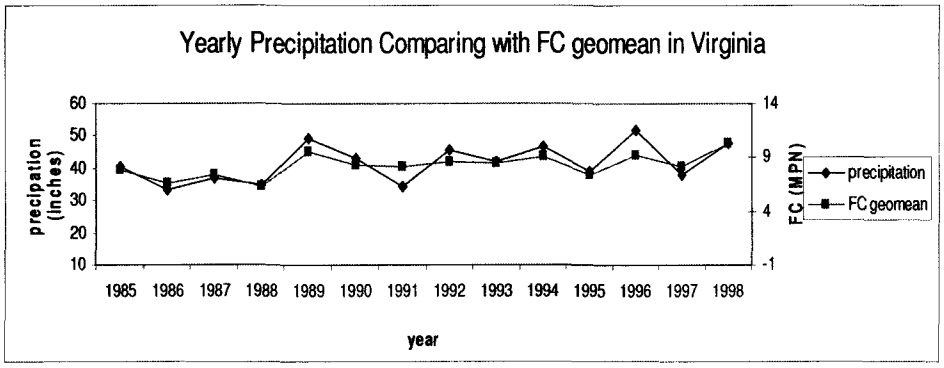


Figure IV-4.6.3: Comparison of FC concentrations and precipitation after grouping rainfall intensity. Precipitation in the first group is a small amount of rain, the intensity of which ranges from 0 to 0.4 inches/day. The second group is medium rain, ranging from 0.4 to 1 inches/day. The third group is large rain, from 1 to 2 inches/day. The fourth and fifth groups are combind as pouring rain, from 2 to 4 inches/day, as well as rainfall greater than 4 inches/day. (The classification is based on the regulations of the China Meteorological Administration.)

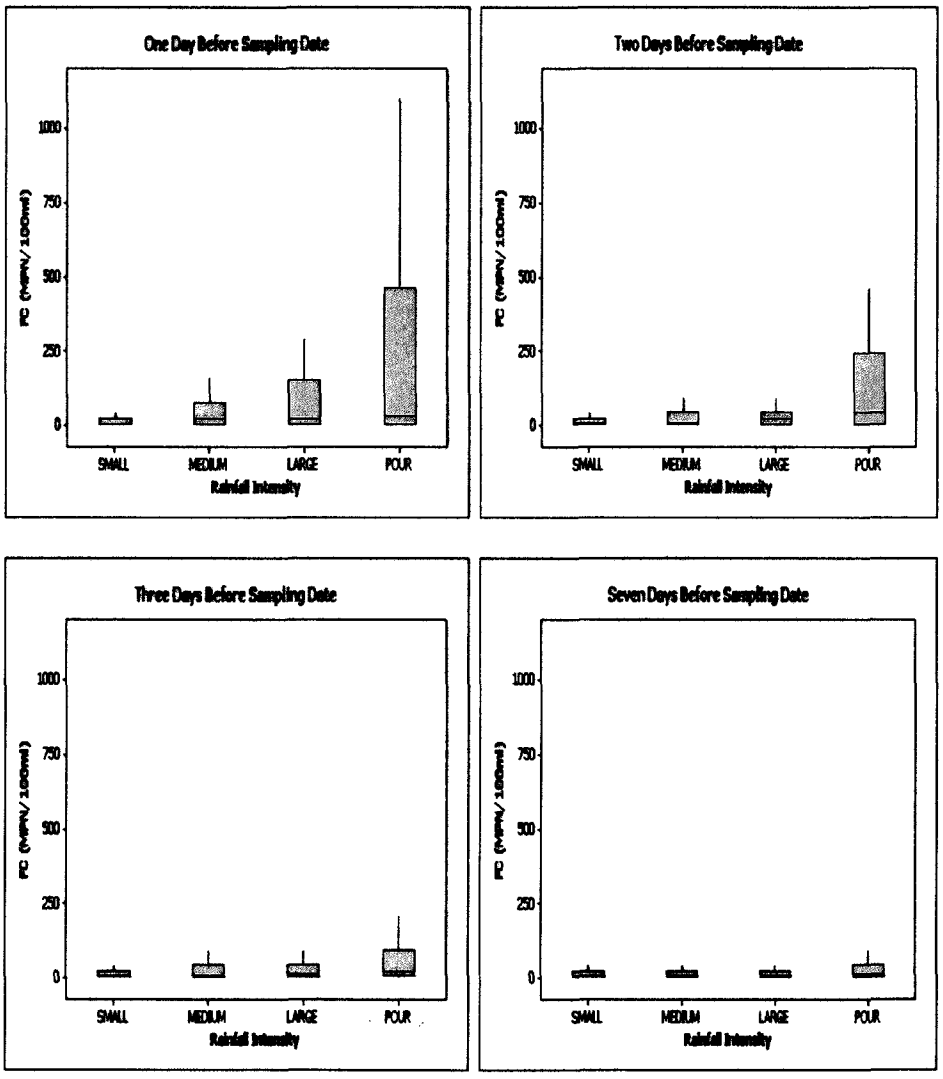
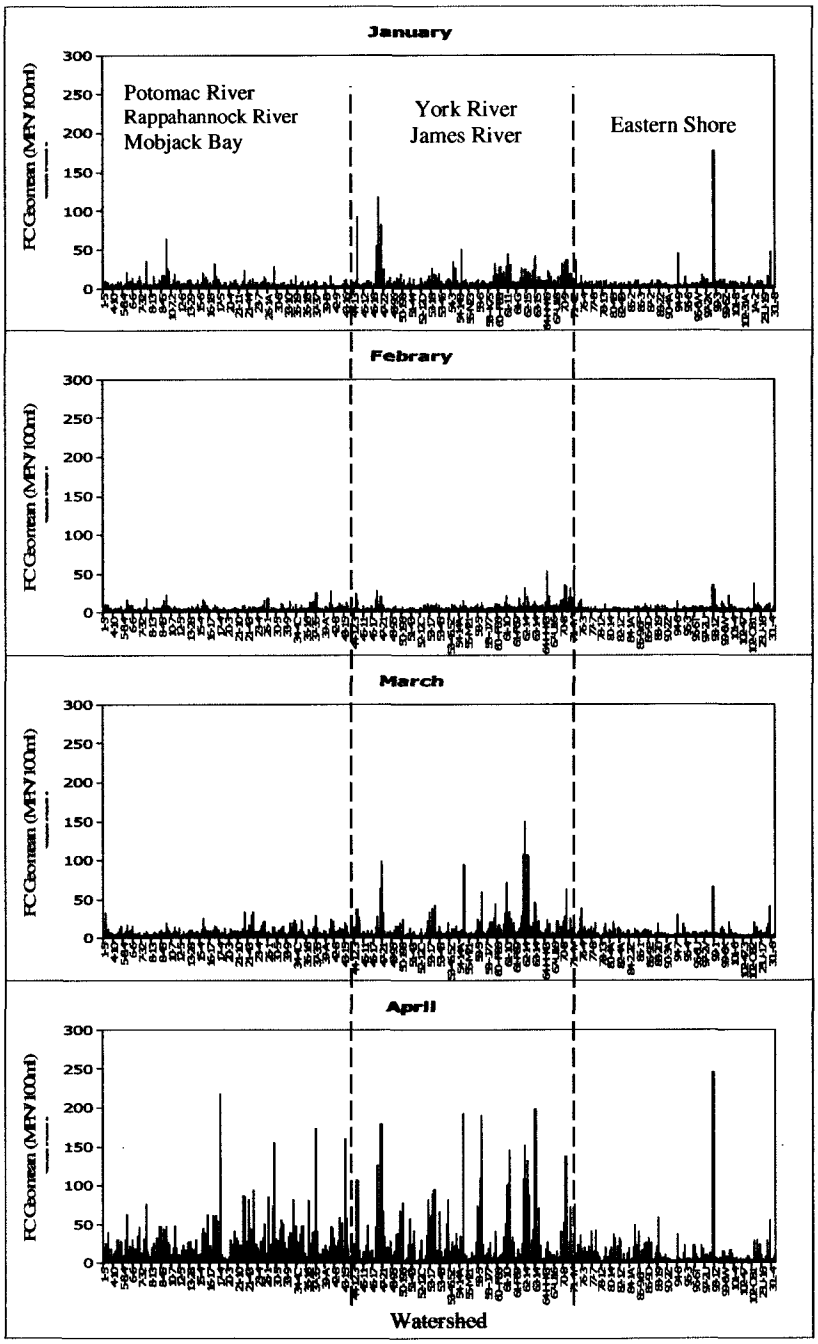
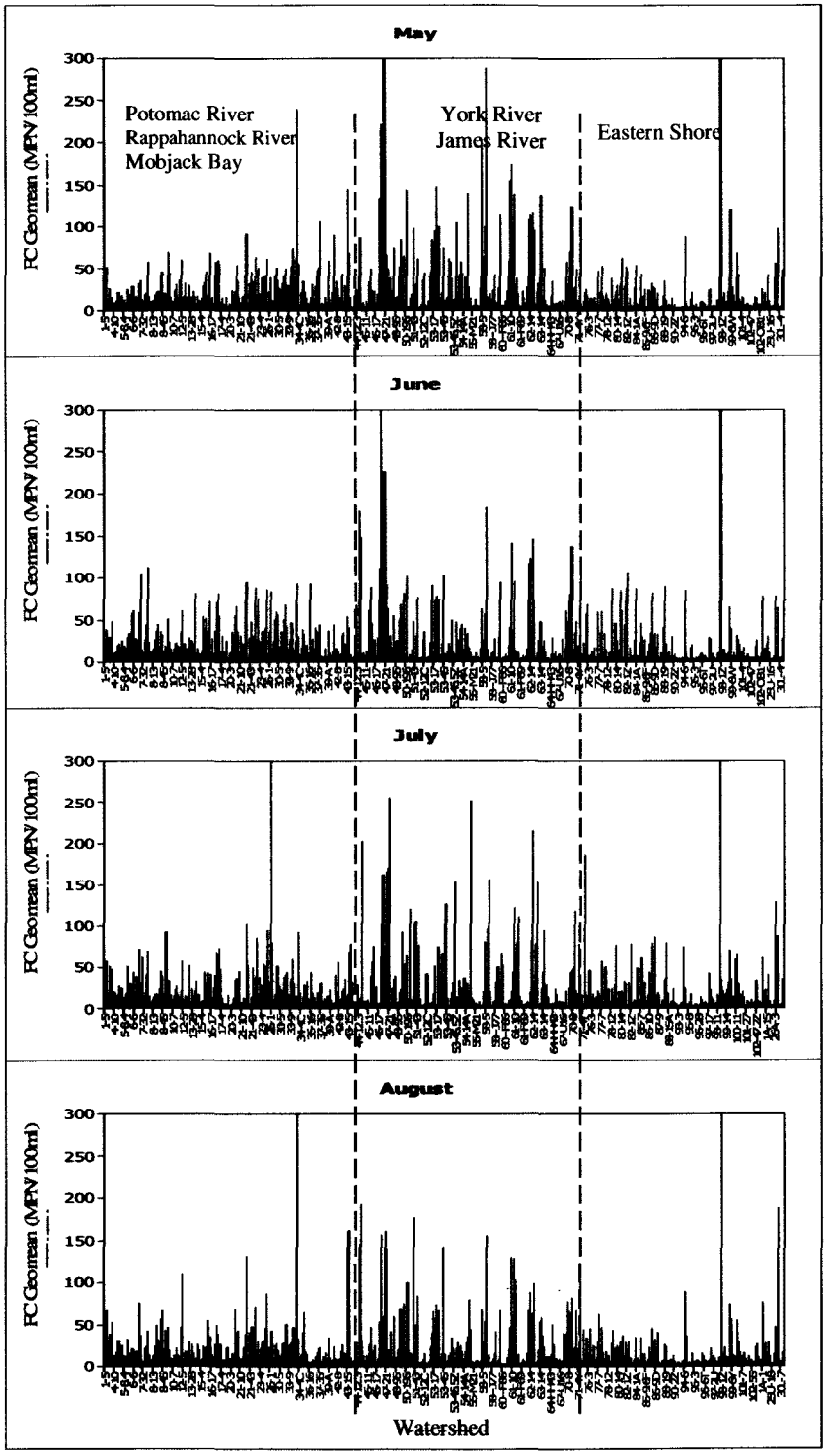


Figure IV-4.6.4: A general temporal pattern of fecal contamination throughout Virginia coastal regions. The red lines separate locations into three groups – 1) Potomac River, Rappahannock River, and Mobjack Bay, 2) York River and James River, and 3) the Eastern Shore .




May
June
July
August
FC Geomean (MPN/100ml)
Potomac River
Rappahannock River
Mobjack Bay
York River
James River
Eastern Shore
Watershed

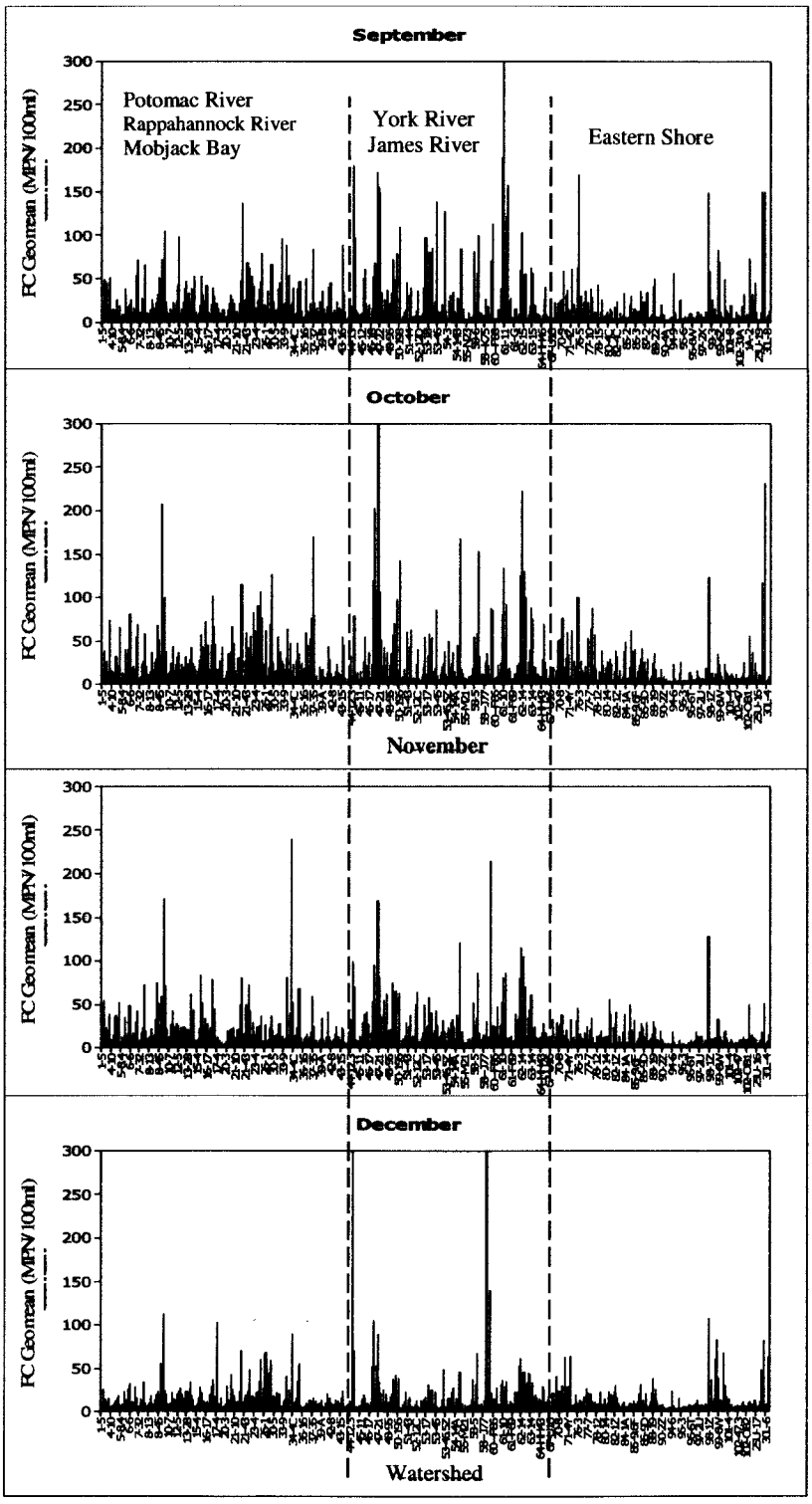
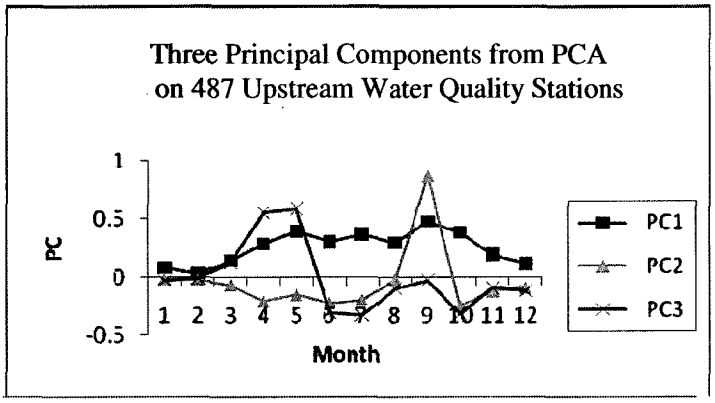
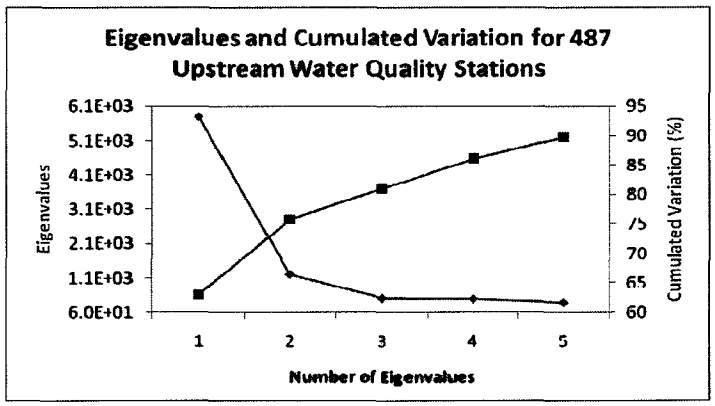

September
Potomac River
Rappahannock River
Mobjack Bay
York River
James River
Eastern Shore
FC Geomean (MPN/100ml)
October
November
December
Watershed

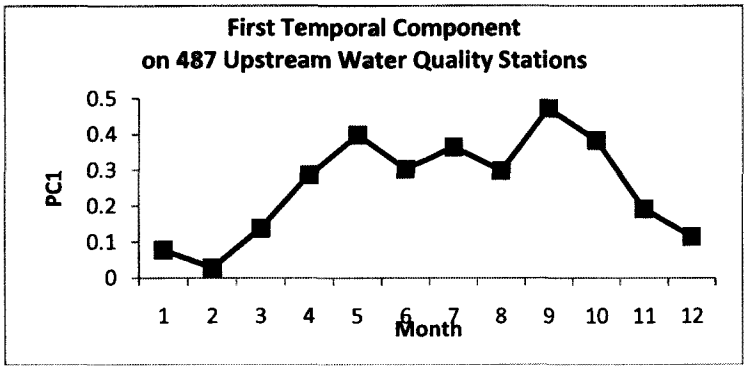
Figure IV-4.6.5. EOF results from 487 upstream water quality stations.
a) First three temporal components with calculated variation; b) First spatial pattern associated with first temporal pattern; c) Second spatial pattern associated with second temporal pattern; d) Third spatial pattern associated with third temporal pattern.

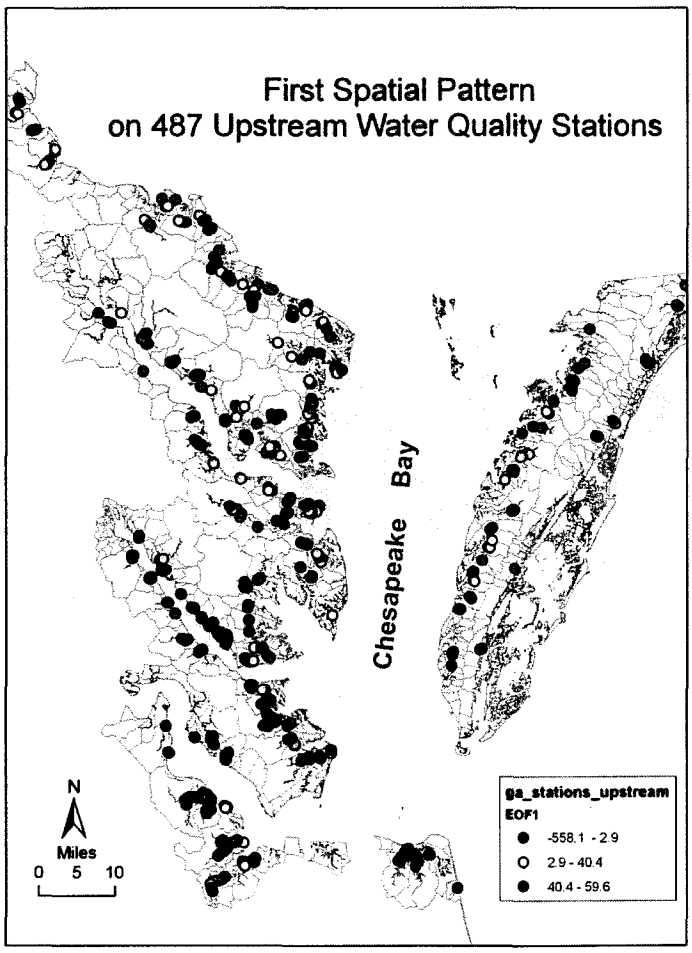
a) First three temporal components with calculated variation



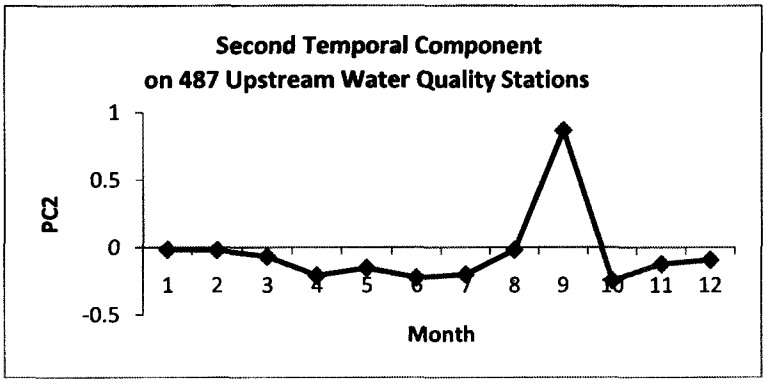


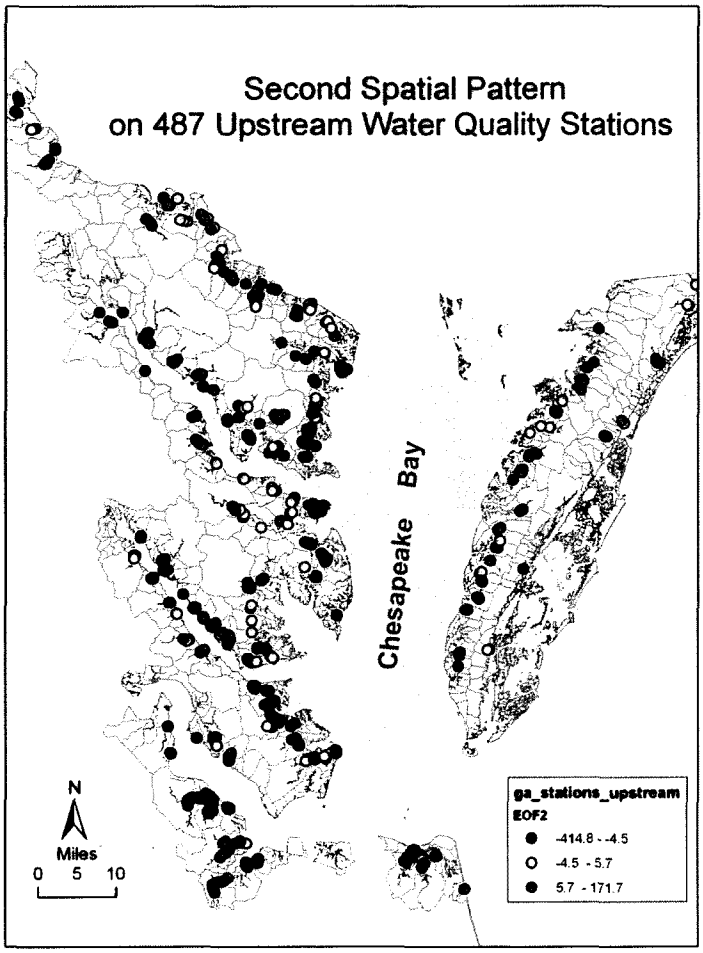
b) First spatial pattern associated with first temporal pattern



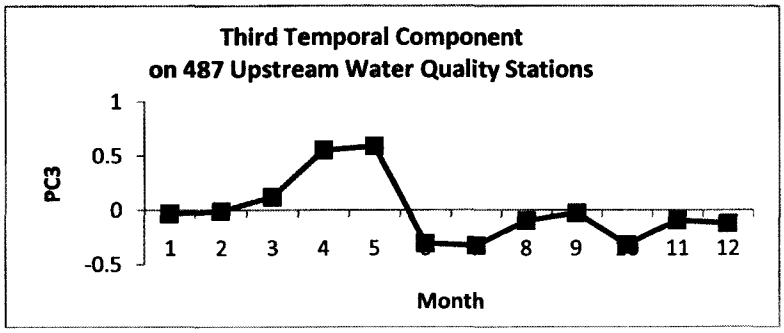


c) Second spatial pattern associated with second temporal pattern





d) Third spatial pattern associated with third temporal pattern



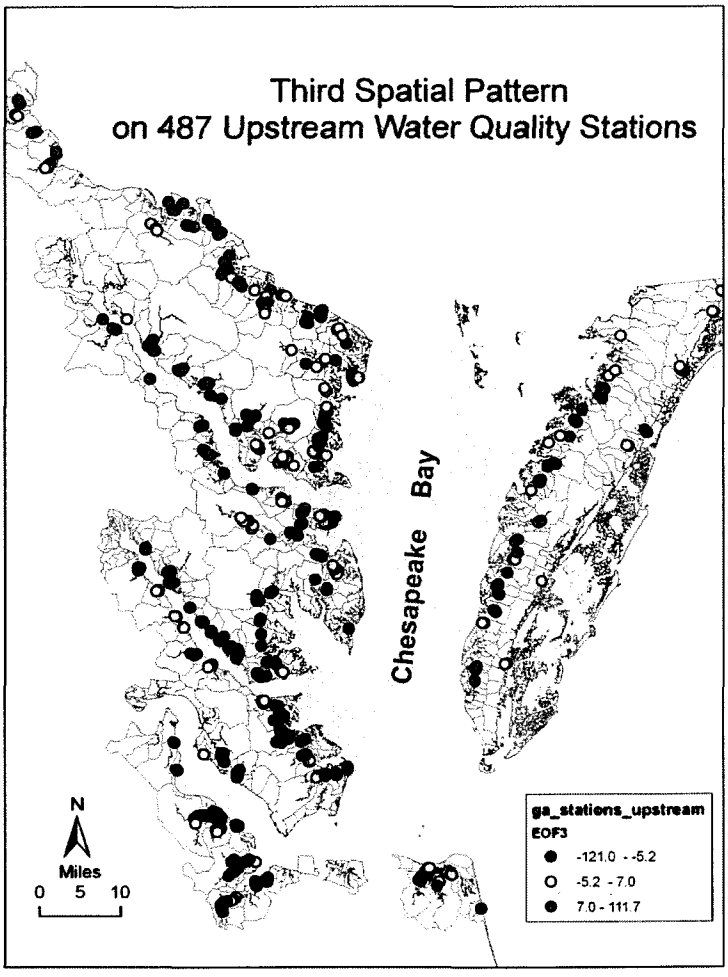
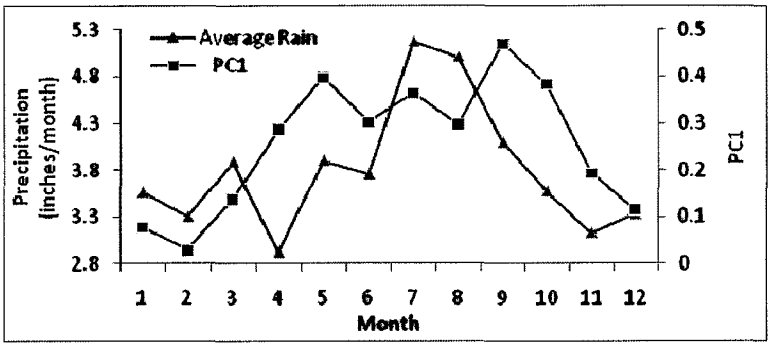
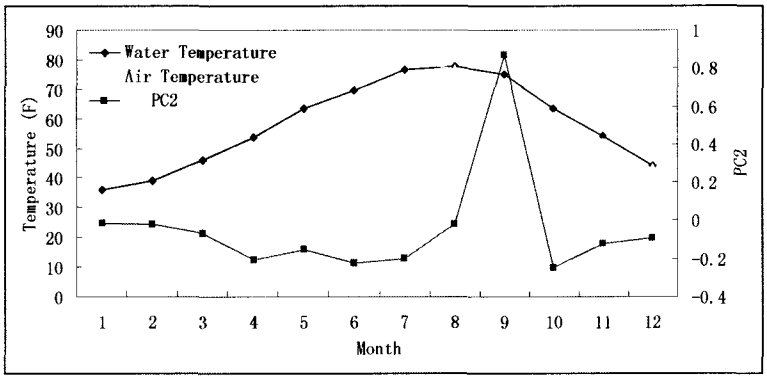


Figure IV-4.6.6: Linkage between the first three PCA temporal components and monthly precipitation, temperature and flow discharge for upstream stations.

a)



b)



c)

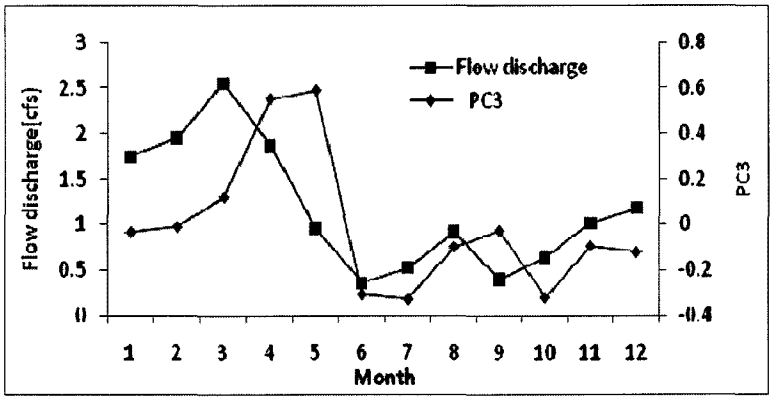


Figure IV-4.7.1: Classification and Regression Tree analysis of FC contamination levels for environmental variables in Virginia coastal regions. Environmental variables listed are ratio (watershed/water area), soil runoff potential, forest percentage, impervious percentage, pasture percentage, wetland percentage, and residence time in the water.

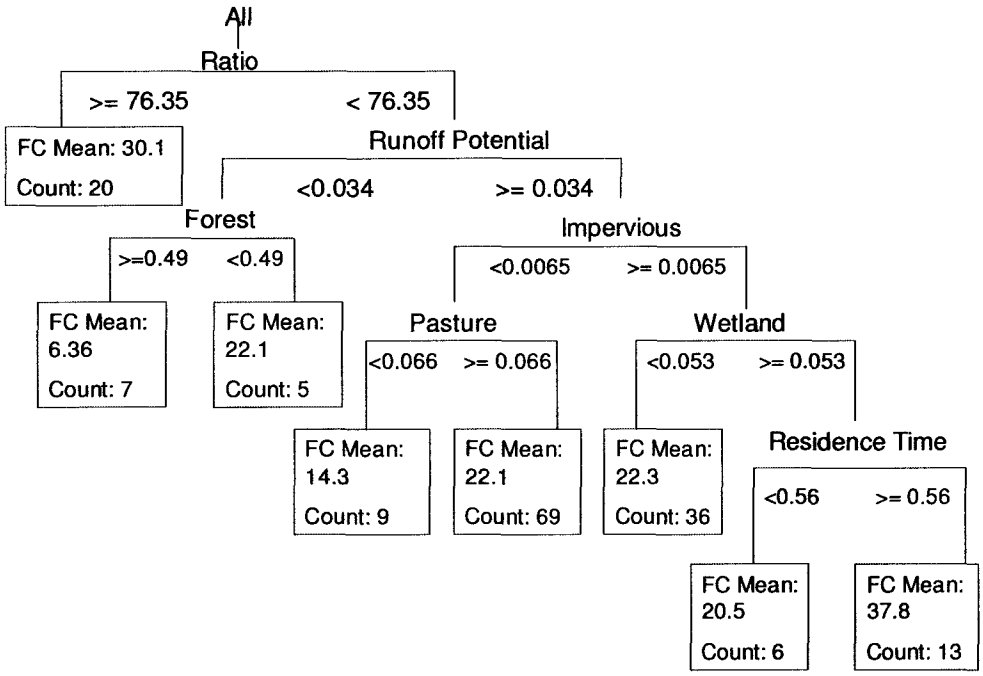


Figure IV-4.7.2: Contributions of environmental variables to fecal contamination levels based on CART analysis. The width of the pink bar indicates the degree of a variable's contribution, with a longer bar representing a greater contribution.

Column Contribution

Term	Number of Splits	SS
Impervious 1990	1	676.626301
Slope	0	0
Drainage density	0	0
Eccentrcity	0	0
Urban	0	0
Forest	1	721.48784
Pasture	1	487.25715
Cropland	0	0
Wetland	1	1258.5196
Ratio	1	1085.40049
Residence time	1	1227.96175
Runoff potential	1	1137.03287
Total	7	6594.28157

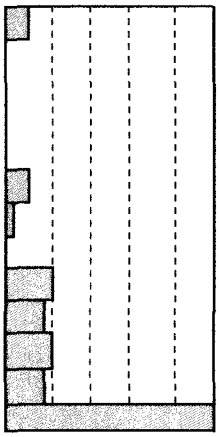


Figure IV-5.3.1: Correlation of percentage of pastureland and percentage of cropland in Virginia coastal regions.

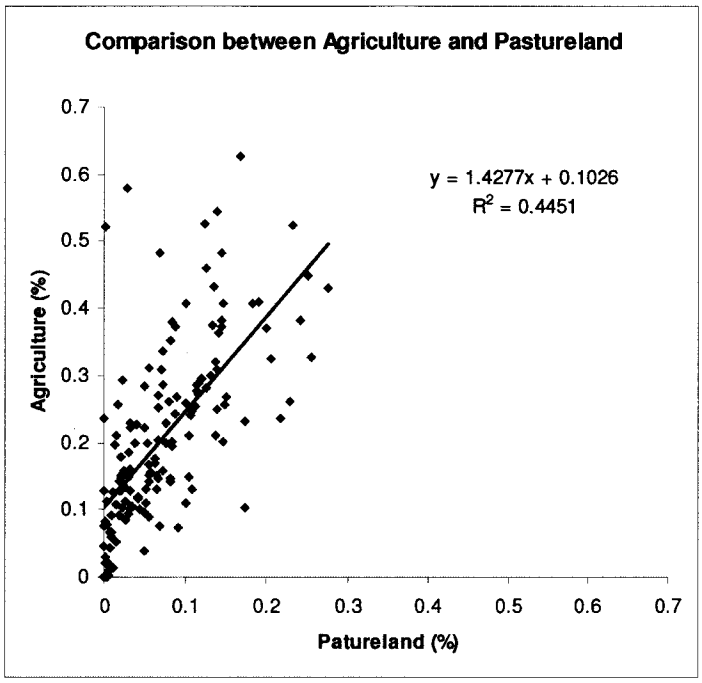


Figure IV-5.3.2: Boxplot comparison of FC concentrations between crop-pastureland-dominated watersheds and forest-dominated watersheds.

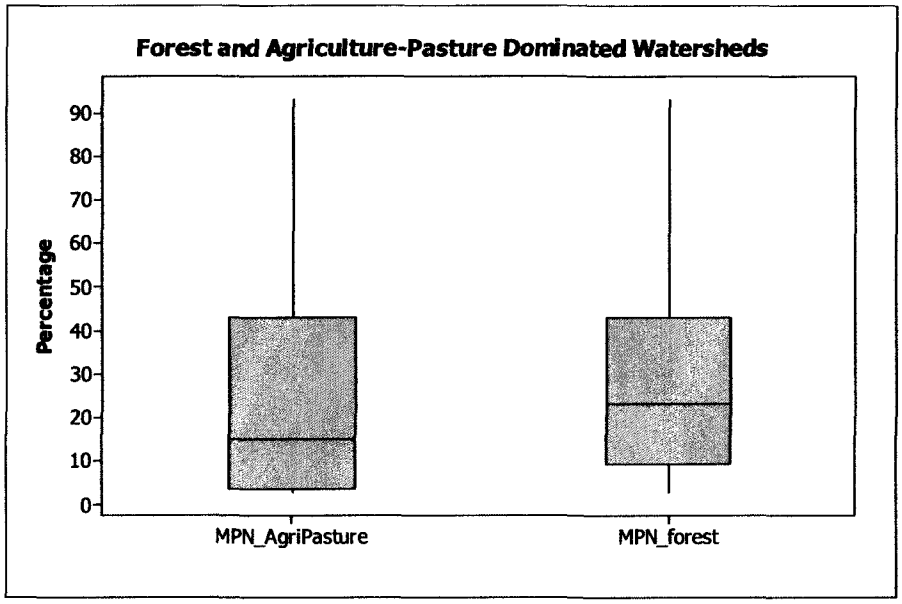


Figure IV-5.4.1: Geometric means of FC bacterial concentrations vs. percentage impervious surface coverage for five coastal watersheds in Southeastern North Carolina (Mallin et al., 2000).

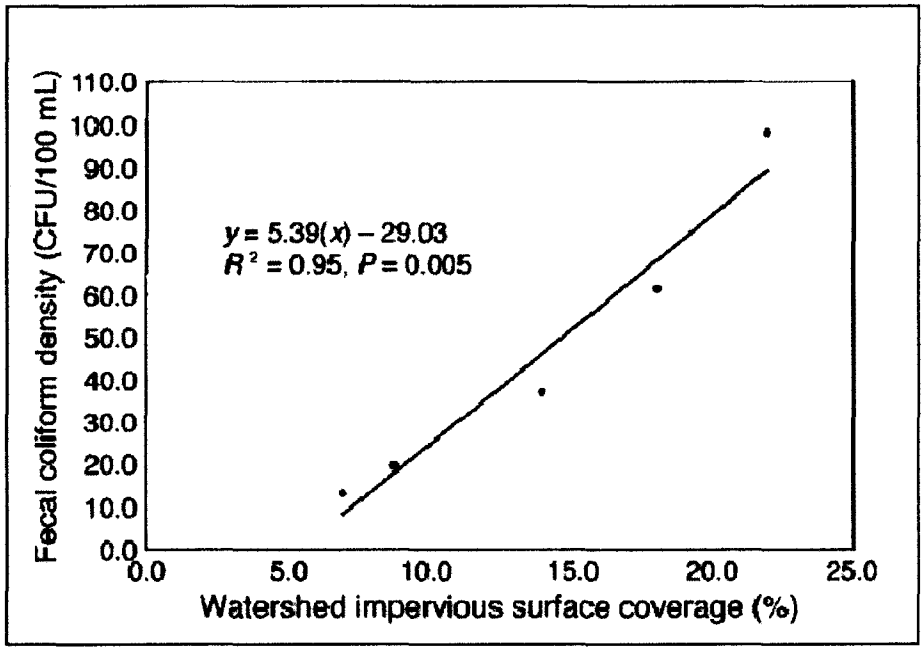


Figure IV-5.5.1: Daily Rainfall Frequency Distribution in 1998 and 1999 based on precipitation data at Norfolk International Airport, VA.

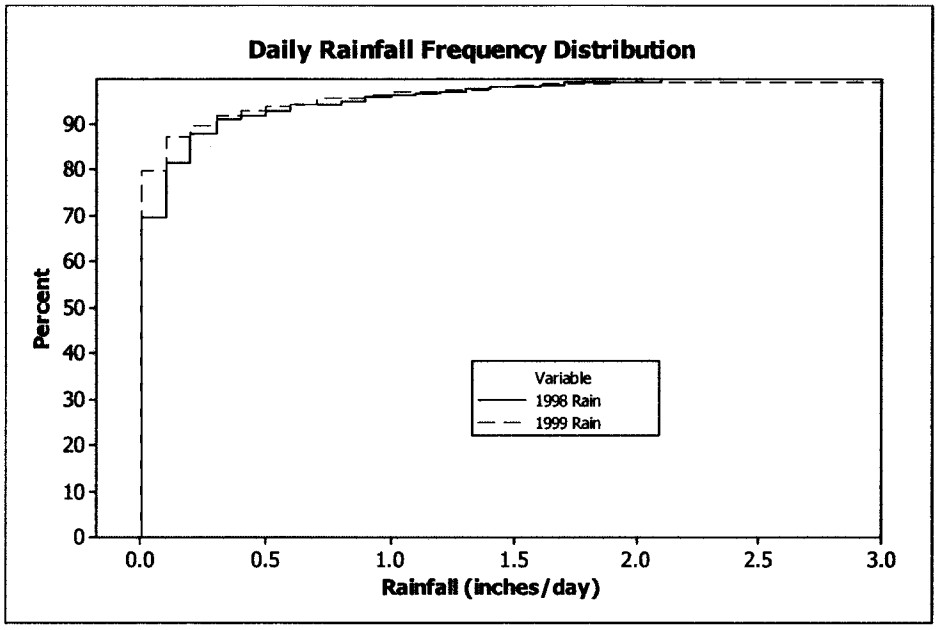


Figure IV-5.5.2: FC concentration frequency distribution divided into various data ranges for different regions (Eastern Shore, Rappahannock River, Potomac River, James River, and York River regions).

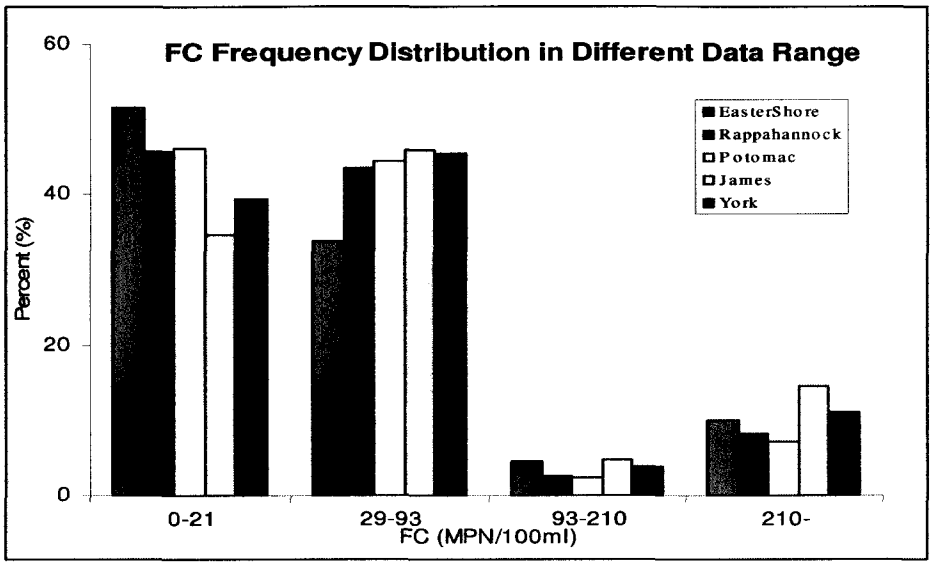
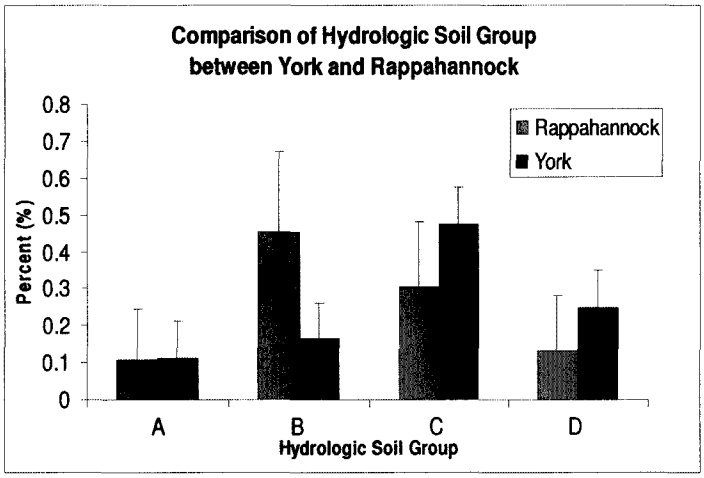


Figure IV-5.5.3: Hydrologic Soil Group comparison between watersheds surrounding the York River and Rappahannock River. Soil data is from the STATSGO database. Group A is characterized by low runoff potential soils, which have a high infiltration rate even when thoroughly wetted. Group B soil has a moderate infiltration rate when thoroughly wetted. Group C has a slow infiltration rate when thoroughly wetted. Group D is high runoff potential soils, which have a very slow infiltration rate when thoroughly wetted.



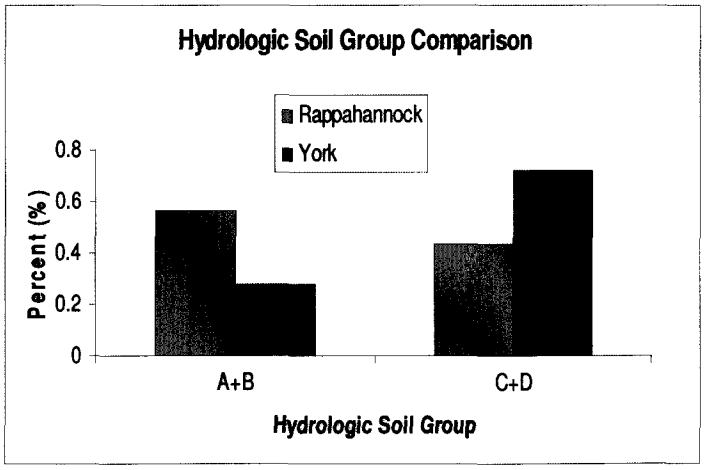


Figure IV-5.6.1: Monthly flow discharge comparison from USGS gaging stations located in headwaters of Rappahannock River, Pamunkey River, and Appomattox River in Virginia.

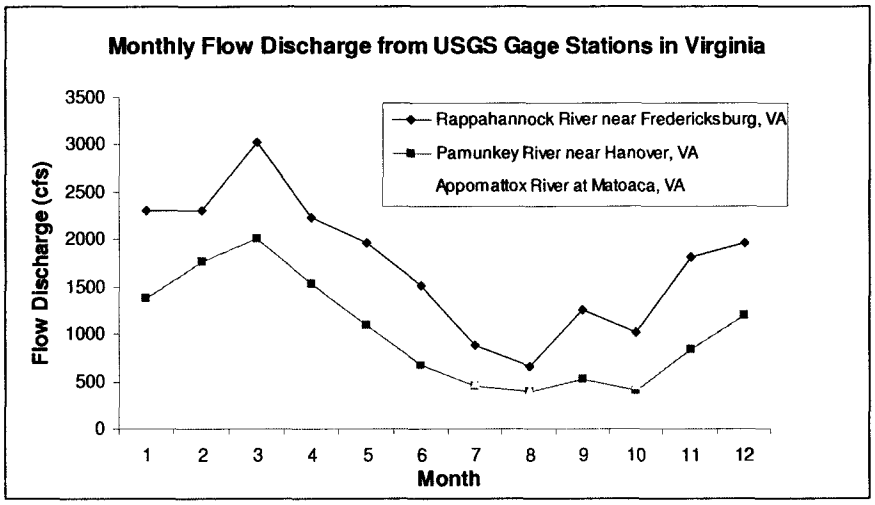


Figure IV-5.6.2: Hurricanes and Tropical Storms in the Atlantic basin. The peak of hurricane season occurs in September in the Atlantic basin according to NOAA hurricane and storm data from 1851 to 2005.

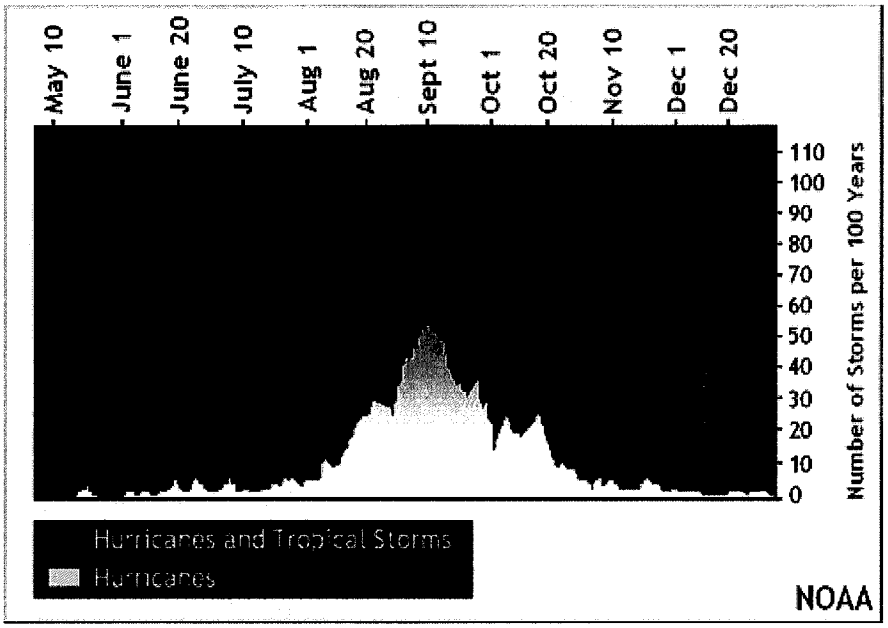
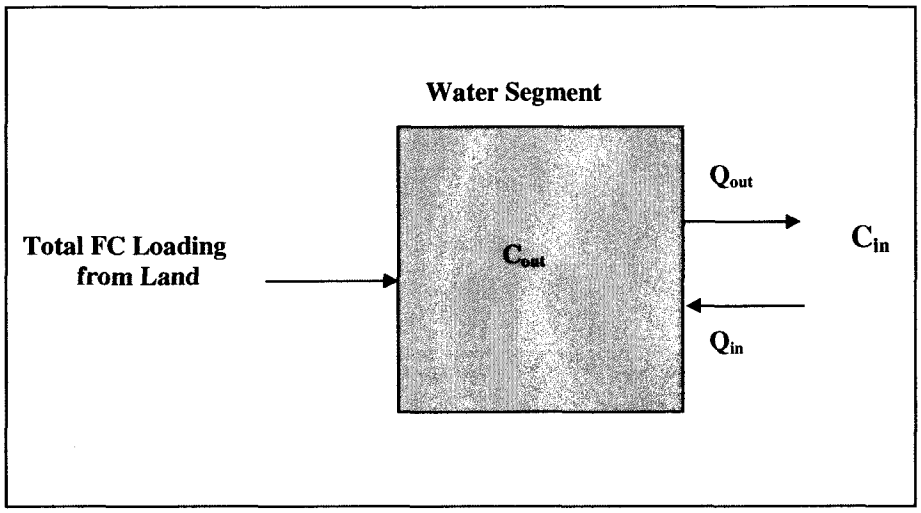


Figure V-2.1 Box model of FC input and output for a water segment located in the headwaters of a river. This single water segment represents a headwater water body, and the fecal bacteria are well mixed in the segment. Characteristics of the transport processes for fecal bacteria depend primarily on the water exchange with downstream areas and water discharge from the watershed land surface.



$$\frac{dVC}{dT} = Q_{in}C_{in} - Q_{out}C_{out} + L_l - kVC_{out}$$

where L_l: Total FC Loadings from land
C_{in}: FC concentration outside of water segment
Q_{in} : Total water volume flow into water segment
C_{out}: FC concentration inside of water segment
Q_{out}: Total water volume flow out of water segment
V : Volume of the water segment (m3)
T : Dominant tidal period (hours)
k : Fecal coliform decay rate (d-1)

Figure V-3.1. Cluster analysis results utilizing Manhattan Distance and Complete Linkage method. Each observation represents an individual watershed and the resulting 5 groups are shown with different colors.

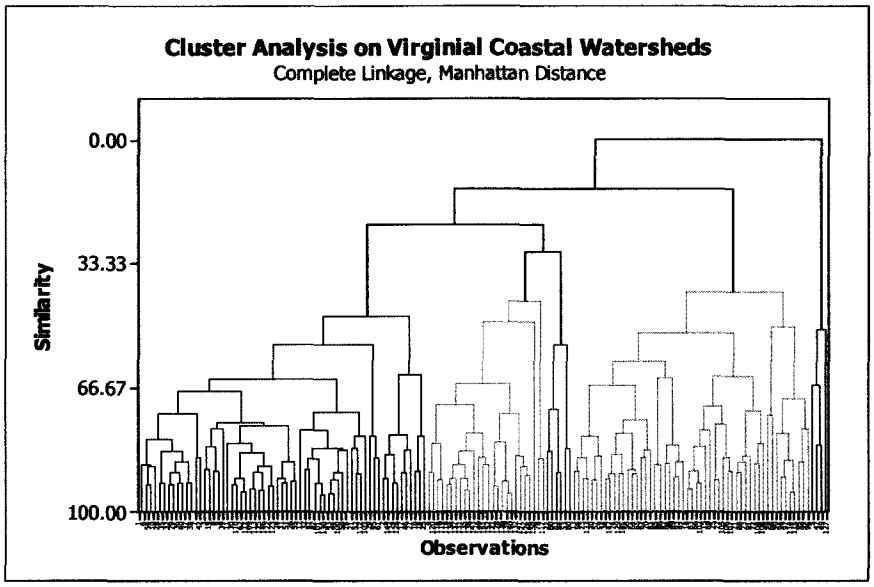
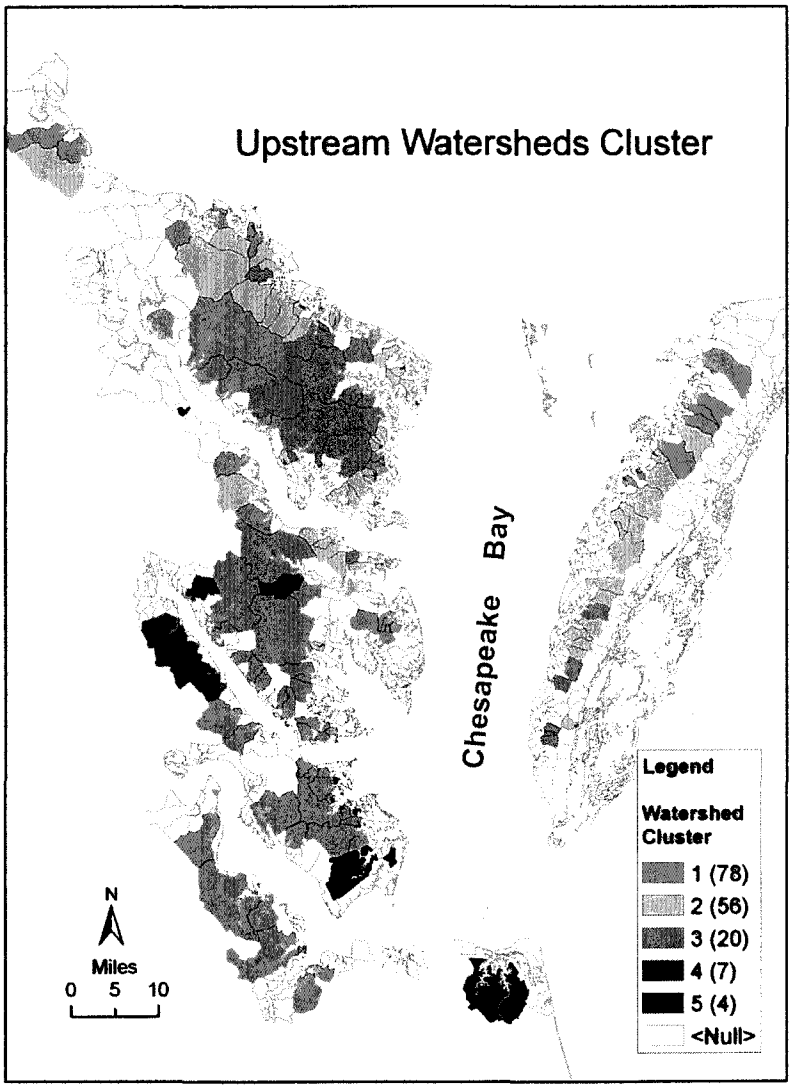
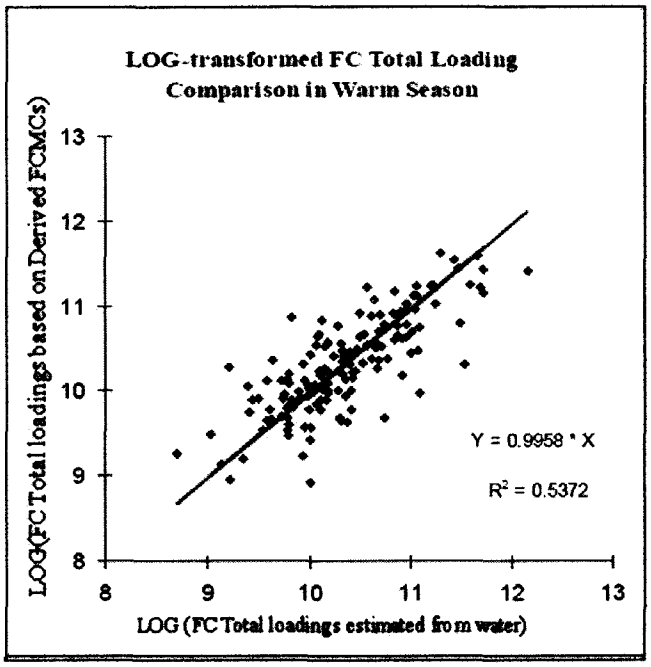


Figure V-3.2: Upstream watersheds groups according to cluster analysis.



Note: The number inside the parentheses is the number of watershed in each cluster.

Figure V-3.4: Comparison of LOG-transformed FC total loadings estimated from water and FC total loadings based on derived FCMCs in warm and cold seasons.



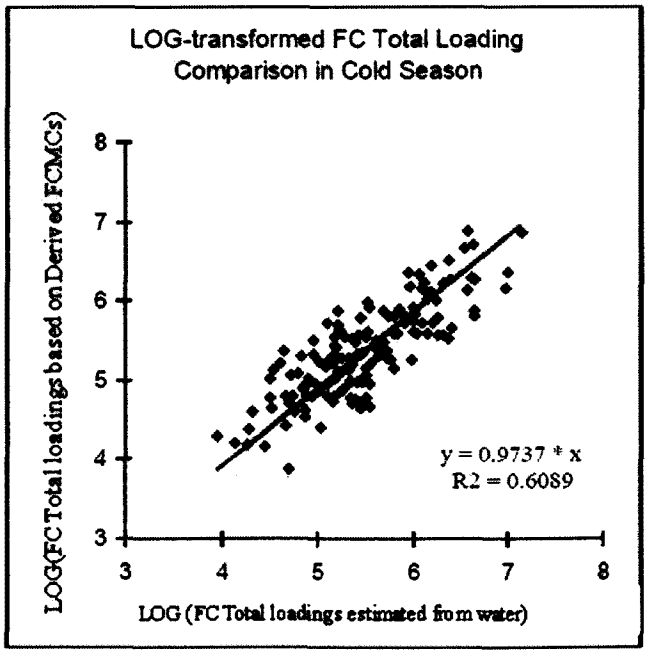


Figure V-3.6. Comparison of FC total loadings estimated from receiving waters and FC total loadings based on derived FCMCs in warm and cold seasons. The red box indicates a watershed with a poor match between estimated total loads from FCMCs and calculated total loads from TPM.

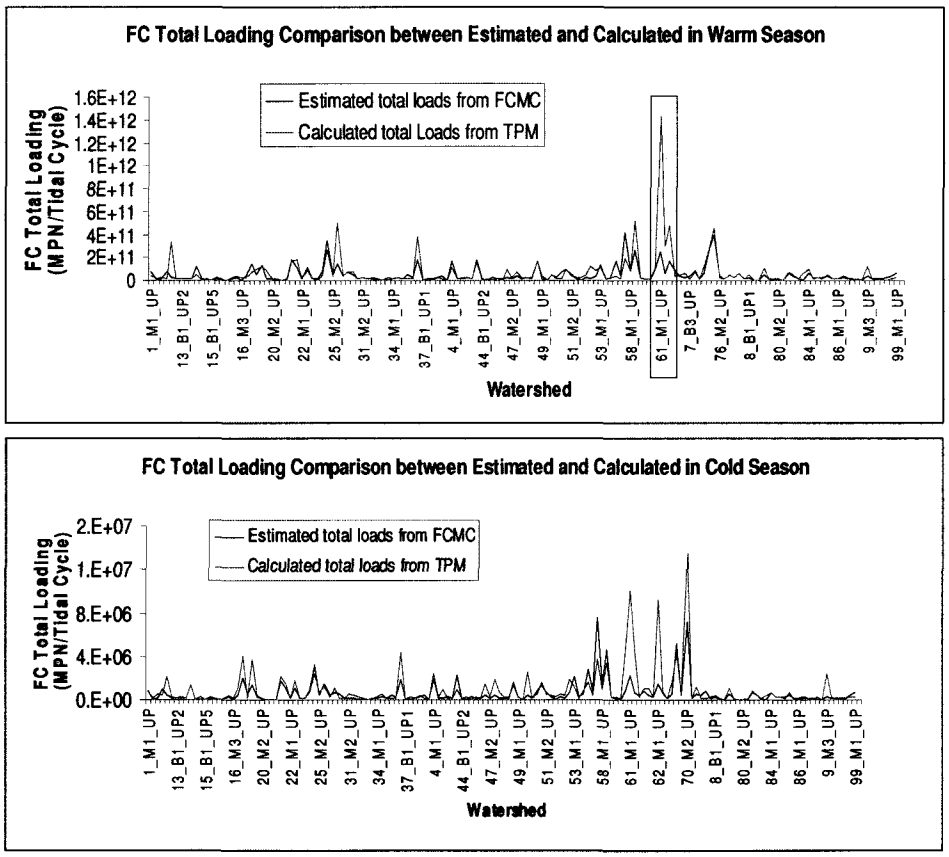


Figure V-3.8. Comparison between FC concentration percentage change and estimated FC total loading percentage change from 1984 to 2005. The percentage change is defined as ratio of the difference between the values in 2005 and 1984 to values in 2005.